

PB 199 427

RADIOMETRIC THERMASONDE™ PROGRAM

FINAL REPORT

Contract No. CPA 22-69-93

Period Covered: 1969 May 15 to 1971 February 15

Project Officer: T. J. Lemmons

Prepared for

DIVISION OF METEOROLOGY
AIR POLLUTION CONTROL OFFICE *
ENVIRONMENTAL PROTECTION AGENCY
RALEIGH, NORTH CAROLINA 27609

*Formerly National Air Pollution Control Administration

SPERRY

MICROWAVE ELECTRONICS DIVISION • CLEARWATER, FLORIDA

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
Springfield, Va. 22151

PB199 427

BIBLIOGRAPHIC DATA SHEET		1. Report No. APTD-0674	2.	3. Recipient's Accession No.
4. Title and Subtitle Radiometric Thermasonde TM Program			5. Report Date February 15, 1971	
			6.	
7. Author(s) T. J. Lemmons (Project Officer)			8. Performing Organization Rept. No.	
9. Performing Organization Name and Address Sperry Microwave Electronics Division Clearwater, Florida			10. Project/Task/Work Unit No.	
			11. Contract/Grant No. CPA 22-69-93	
12. Sponsoring Organization Name and Address Division of Meteorology Air Pollution Control Office Environmental Protection Agency Raleigh, North Carolina 27609			13. Type of Report & Period Covered Final	
			14.	
15. Supplementary Notes				
16. Abstracts This report is a summary of contract requirements and work performed on the Radiometric THERMASONDE Program. Included are equipment specifications, requirements and block diagrams of the MK II THERMASONDE. Details of some work are included in this report as are references to other reports on this contract and associated reports from other sources. This work culminated in a MK II THERMASONDE configuration with many critical design details completed and recommendations for continuing development effort.				
17. Key Words and Document Analysis. 17a. Descriptors Thermal measuring instruments Radiation measuring instruments Equipment specifications Design criteria Calibrating Maintenance Education				
17b. Identifiers/Open-Ended Terms Thermasonde Air pollution measurement				
17c. COSATI Field/Group 20/F, 13/B				
18. Availability Statement Unlimited		19. Security Class (This Report) UNCLASSIFIED		21. No. of Pages 69
		20. Security Class (This Page) UNCLASSIFIED		22. Price

RADIOMETRIC THERMASONDETM PROGRAM

FINAL REPORT

Contract No. CPA 22-69-93

Period Covered: 1969 May 15 to 1971 February 15

Project Officer: T. J. Lemmons

Prepared for

**DIVISION OF METEOROLOGY
AIR POLLUTION CONTROL OFFICE *
ENVIRONMENTAL PROTECTION AGENCY
RALEIGH, NORTH CAROLINA 27609**

***Formerly National Air Pollution Control Administration**

SJ 232-6062-15

Copy No. _____

ACKNOWLEDGEMENT

The work upon which this publication is based was performed pursuant to Contract No. CPA22-69-93 with the Air Pollution Control Office, Environmental Protection Agency, which at the time of contract award was designated National Air Pollution Control Administration, CPE, Public Health Service, Department of Health Education and Welfare.

ABSTRACT

This report is a summary of contract requirements and work performed on the Radiometric THERMASONDE Program. Included are equipment specifications, requirements and block diagrams of the MK II THERMASONDE. Details of some work are included in this report as are references to other reports on this contract and associated reports from other sources. This work culminated in a MK II THERMASONDE configuration with many critical design details completed and recommendations for continuing development effort.

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1.	SUMMARY	1-1
2.	INTRODUCTION AND BACKGROUND	2-1
2.1	Contract Development and Summary	2-1
2.2	Publications Issued Under Contract	2-3
2.3	Technical Background	2-3
2.3.1	General	2-3
2.3.2	Requirements	2-4
2.4	References	2-6
3.	MK I THERMASONDE FOLLOWUP	3-1
3.1	Introduction	3-1
3.2	Maintenance and Field Service	3-1
3.3	Calibration	3-2
3.4	Training Material and Assistance	3-2
3.5	MK I Sensitivity Improvement	3-3
4.	DEVELOPMENT OF THE MK II THERMASONDE CONFIGURATION	4-1
4.1	Introduction	4-1
4.2	Advanced Design Requirements Investigation	4-9
4.2.1	Automatic Gain Control	4-9
4.2.2	Demodulator	4-10
4.2.3	X-Y Recorder	4-10
4.2.4	Source Temperature Computer	4-10
4.2.5	Video Tracking Filter and Chopper Drive	4-10
4.2.6	Height Function Generator	4-11
4.2.7	Solid State Local Oscillator	4-11
4.2.8	Antenna Design Requirements	4-11
4.3	Preliminary Design	4-13
4.3.1	Introduction	4-13
4.3.2	Specifications	4-13
4.3.3	System Configuration	4-15
4.3.4	Design Details	4-18

TABLE OF CONTENTS (Continued)

<u>Section</u>		<u>Page</u>
5.	CONCLUSIONS AND RECOMMENDATIONS	5-1
5.1	Conclusions	5-1
5.2	Recommendations	5-1
APPENDIX A	Automatic Gain Control	A-1
APPENDIX B	Measurement Error Budget	B-1

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
4-1	MK II THERMASONDE, Unitary System	4-2
4-2A	MK II THERMASONDE Outdoor Unit	4-3
4-2B	MK II THERMASONDE Control Unit	4-3
4-3	MK II THERMASONDE Control Unit	4-6
4-4	MK II THERMASONDE, Basic Block Diagram	4-7
4-5	MK II Control Unit, Preliminary Block Diagram	4-27
4-6	Typical Recording for Automated Sounding	4-30

1. SUMMARY

The work reported here was performed by Sperry Microwave Electronics Division of Sperry Rand Corporation, Clearwater, Florida, under Contract No. CPA22-69-93 for the Air Pollution Control Office of the Environmental Protection Agency (formerly NAPCA, DHEW).

The work content included some follow-up tasks relative to the MK I Radiometric THERMASONDE delivered to NAPCA under an earlier contract, sensitivity improvement and refurbishment of the MK I, and design requirements investigation and preliminary design for an advanced model THERMASONDE designated MK II.

All work was on a best-efforts basis under the close technical supervision of Mr. T. J. Lemmons, APCO Project Officer, since it was expected that changes in the program details would be desired from time to time to take advantage of technical advancements in hardware or improved knowledge of equipment requirements being developed elsewhere.

All work relative to the MK I was carried out successfully and significant improvement made in MK I sensitivity. The design requirements investigation and preliminary design were carried to the point where an optimized configuration has been established. Critical portions of the equipment design are ready for breadboard fabrication and development.

The progress to date in configuration development and the development of data translation techniques fully justifies a recommendation for a program to complete the MK II development, fabrication, and field evaluation.

2. INTRODUCTION AND BACKGROUND

2.1 CONTRACT DEVELOPMENT AND SUMMARY

Contract No. CPA22-69-93, entitled Radiometric THERMASONDE Program, had an effective start date of 15 May 1969 and a scheduled completion in 12 months. The contract was later modified to add additional work and the schedule was extended to 21 months. This contract was for follow-on effort to Contract Nos. PH86-67-76 and PH22-68-22, entitled "Capabilities of Millimeter Wave Radiometers for Remotely Measuring Temperature Profiles Pertinent to Air Pollution." These contracts were awarded to the Sperry Rand Research Center (SRRC), Sudbury, Massachusetts, but Sperry Microwave Electronics Division (SMED), under subcontract to SRRC on the latter contract, designed, developed and delivered to NAPCA, the MK I Radiometric THERMASONDE. The final report on Contract No. PH22-68-22, entitled "Development of MK I Radiometric THERMASONDE and Simulation and Experimental Studies for Passively Probing Temperature Structure within the First Mile of the Atmosphere," SRRC Report No. SRRC-CR-70-6, covers development of the MK I THERMASONDE.

The original scope of work under contract CPA22-69-93 included the following items (in addition to monthly, quarterly and final reports):

Phase I

- Calibrate the MK I at the additional frequencies of 54.0 and 55.0 GHz. Check original calibration at 54.5 GHz.
- Provide maintenance and field support for MK I operation by NAPCA.

Phase II

- Provide instructions and educational material to support NAPCA's training program at the Research Triangle Park, N.C. Two courses were scheduled.
- Investigate advance design requirements for MK II THERMASONDES, both electrical and mechanical, with special emphasis on development of SMED's automatic gain control (AGC) technique which would permit completely automated equipment operation.

Phase III

Engineering design of MK II, an outgrowth of the results of Phases I and II and analytical inputs from SRRC. Phase IIIA, Preliminary Design, was not implemented in original contract.

Before completion of all the work called for under the contract, it was decided by NAPCA that an improvement in sensitivity of the MK I should take precedence over some parts of the requirements investigation. (Independent development by SMED had proven a significant sensitivity improvement could be attained.) A contract modification (Mod 2) was issued which provided for reducing some work originally called for and substituting sensitivity improvement.

Contract Modification No. 1 was also issued which provided for implementation of program Phase IIIA, Preliminary Design. In accordance with Mod 1, the period of performance was extended to 21 months and the Statement of Work modified to implement Phase IIIA, Preliminary Design, only. At the same time previous requirements for monthly reports were deleted.

Under the contract, as modified, the MK I was recalibrated, some minor repairs made to it (largely necessitated by shipping damage), and the receiver front end modified to improve sensitivity. MK I training materials were provided to NAPCA and a single lecture and demonstration given at Research Triangle Park. The requirements investigations, started under the unmodified original contract but not completed due to contract modification, were carried further under the modified contract as part of Preliminary Design. Under the Preliminary Design Phase (IIIA), detailed design of major portions of MK II were completed and engineering information packages generated for all critical areas. Phase IIIA did not include any fabrication or breadboard testing of designs. The present status of MK II design is such that physical development of the engineering model may be undertaken as soon as authorized.

2.2 PUBLICATIONS ISSUED UNDER CONTRACT

The following publications were issued under contract CPA22-69-93:

- Monthly Progress Reports, No. 1 through 8 covering the first, second, fourth, fifth, seventh, eighth, tenth and eleventh months. (Monthly reports were not issued during the same months as quarterly reports.)
- Radiometric THERMASONDE Program. Quarterly Progress Reports, numbered first through sixth, issued in the months of August and November 1969, and February, May, August and November 1970.
- MK I THERMASONDE Training Material, SMED No. SJ232-6062-2, issued in September 1969.
- Task Description, MK I THERMASONDE Sensitivity Improvement, SMED No. SJ232-6062-9, issued in February 1970.
- "Handbook of Instructions for Radiometric THERMASONDE, MK I," Revised, September 1970, SMED No. 232.3813.AO5410. (Originally issued March 1969, revised 1970 to show changes made during sensitivity improvement and new calibration charts.)

2.3 TECHNICAL BACKGROUND

2.3.1 General

A THERMASONDE (previously Radiometric THERMASONDE) is a specialized piece of electronic equipment for probing the thermal structure of the atmosphere. More precisely, it is a microwave radiometer specifically designed to measure the emission brightness temperature of atmospheric oxygen molecules within a portion of the microwave spectrum (≈ 50 to 70 GHz). In this portion of the spectrum, oxygen has strong spectral emissions. The temperature measurements are made either as a function of elevation angle or frequency or both, and produce data from which the existing temperature versus height profile may be derived to a reasonable approximation.

Three advanced radiometric data analysis techniques have been under investigation and analysis by SRRC. A combined experimental and analytical approach was taken so that neither the signal processing nor hardware techniques imposed unrealistic demands upon the other. This allowed the results from each to aid in understanding

and improving the other. In this light, SMED has established a reasonable set of required hardware parameters which permits data output suitable for several data translation techniques.

The contract effort which is the subject of this report was primarily in the hardware design area; consequently, this report is mainly concerned with that hardware. For details of probing theory and study effort in THERMASONDE data translation techniques, the reader is referred to various reports^{1,2,3,4,5} published by the Sperry Rand Research Center and others.

Reference 2 also contains some introductory material on microwave radiometry for the reader who may not be familiar with the subject.

2.3.2 Requirements

It has been established that for the data translation techniques to work effectively, the measured brightness temperature versus elevation angle versus frequency must have a high level of accuracy. The operating mode used in the MK I THERMASONDE and presently planned for the MK II is one in which the brightness temperature is recorded as the antenna-receiver unit is scanned from zero to 90 degrees elevation while the operating frequency is held at a constant frequency within the 54.0 to 55.0 GHz range. The frequency is only changed to compensate for atmospheric density changes caused by changing to operating sites of quite different altitudes (or, as in the past, for purely experimental reasons).

Accurate measurement of brightness temperature for probing purposes requires that the measuring circuits themselves have excellent stability. It also requires that the operating frequency be stable and known within a few MHz. It further requires that the elevation angle be accurately known and that the antenna have minimum radiation outside the main lobe and be accurately boresighted. The details of error budgeting are covered in other sections where accuracy of indicated brightness temperature is related to error sources. At this point it is perhaps sufficient to say that the design goal absolute accuracy of $\pm 0.5^{\circ}\text{C}$, stated as necessary for some data translation techniques, is a quite sufficient goal from a practical engineering viewpoint. This will be better appreciated when it is understood that the stated error includes not only instrumental errors (gain variations, nonlinearity errors, frequency error, boresight or

pointing errors, and antenna error) but calibration errors as well. The problem is further complicated by the necessity for the most critical components to operate outdoors anywhere in the U.S.A. during all seasons and maintain accuracy over long periods of time without recalibration. Further, it must withstand shipment, must be protected from radio frequency interference and operate from relatively unstable power sources.

The general set of environments applicable to MK II THERMASONDE design are summarized in the following paragraphs.

Supply Voltage/Frequency. The THERMASONDE shall operate within specifications from any single-phase ac power source of adequate power rating whose voltage is within the range of 105 to 125 volts and whose frequency does not vary outside the range of 57 to 63 Hz.

Temperature. Except for the control unit and recorder, the THERMASONDE shall operate within specifications outdoors, during all seasons of the year, in darkness or full sunlight, for ambient temperatures in the range of -35 to $+40^{\circ}\text{C}$. The control unit and recorder shall operate indoors in the ambient temperature range of 4 to 35°C (40 to 95°F).

Shock and Vibration. The equipment shall survive the shock and vibration normally encountered in shipment by rail, truck, air, or ship. After such transport, the equipment shall be capable of setup and operation within specifications.

Altitude. The equipment shall operate within specifications at observing sites ranging in elevation from sea level to 3000 feet.

Humidity. The equipment shall suffer no damage from extended exposure to relative humidity up to 100 percent and shall operate within specifications during such exposure. Errors due exclusively to expansion of chart paper or improper inking under such conditions shall not constitute failure within the meaning of this specification.

Precipitation. Those portions of the equipment designed for operation out of doors shall suffer no damage or degradation in performance from extended exposure to precipitation in the form of rain or snow, whether operating or not, when fully assembled in its normal operating orientation; however, measurements to specification accuracy shall not be required during such precipitation nor for one-half hour thereafter.

Radio Frequency Interference. The equipment shall be designed for exclusion of radiated and conducted radio frequency interference. The receiver, particularly, shall be made essentially RFI tight. The input and output lines, where appropriate, shall be filtered for protection against conducted RFI, line transients, and noise.

2.4 REFERENCES

1. Mount, W.D., et al: "Three Radiometric Data Analysis Techniques for Measuring Air Temperature Profiles," Final Report on Contract No. CPA22-69-116, Sperry Rand Research Center Report No. SRRC-CR-70-27
2. Mount, W.D., et al: "Development of Mark I Radiometric ThermasondeTM and Simulation and Experimental Studies for Passively Probing Temperature Structure Within the First Mile of the Atmosphere," Final Report on Contract No. PH22-68-22, Sperry Rand Research Center Report No. SRRC-CR-70-6
3. Mount, W.D., et al: "Investigation of the Capabilities of Millimeter Wave Radiometers for Remotely Measuring Temperature Profiles Pertinent to Air Pollution," Final Report on Contract No. PH86-67-76, Sperry Rand Research Center Report No. SRRC-CR-68-19
4. Westwater, E.R.: "Ground-based Determination of Temperature Profiles by Microwaves," Doctorial Thesis, Univ. of Colorado, Dept. of Physics and Astrophysics, 1970
5. Westwater, E.R., and O.N. Strand: "Application of Statistical Estimation Techniques to Ground-based Passive Probing of the Tropospheric Temperature Structure," ESSA Technical Report IER37-ITSA37

3. MK I THERMASONDE FOLLOWUP

3.1 INTRODUCTION

Included in this contract were certain tasks related to the MK I THERMASONDE which was developed on a previous contract and delivered in February 1969. These tasks included additional calibration, maintenance and field service, sensitivity improvement, and training materials and assistance, all as described in section 2.1. This section is a summary of work performed and, where applicable, results obtained in those areas of effort.

3.2 MAINTENANCE AND FIELD SERVICE

On the whole, the equipment was found to be sufficiently reliable that no maintenance or field service were required of SMED prior to December 1969. At that time, the equipment sustained minor mechanical damage in shipment to California for field tests. The THERMASONDE was checked out and such repairs as necessary made on site by the SMED engineer participating in the tests. Damage did not interfere with the test program.

In mid February 1970, the THERMASONDE was returned to SMED both for additional calibration previously scheduled and for complete checkout and refurbishing. Checkout showed operation of the THERMASONDE to be the same as when shipped a year earlier. The repairs of mechanical damage were completed.

During further operation of the THERMASONDE, two electrical faults were found. One was a poor connection on the video-amplifier circuit board which caused a shock sensitive change in output when the receiver unit was operated upside down. The other was an open circuited RFI filter in the common (ground) circuit to the recorder. The reason for filter failure was not determined with any certainty, but it is presumed that it was burned out by accidental connection of the common lead to a recorder having an ungrounded "hot" chassis during some field operation. Neither of these faults had been evident during field operations nor caused any known measurement errors. The

first fault could have caused erroneous measurements under certain conditions, but apparently never did. The second fault would only result in a somewhat noisier data output under certain conditions but no actual errors.

3.3 CALIBRATION

Calibration at additional frequencies of 54.0 and 55.0 GHz and check of calibration at 54.5 GHz was accomplished as required. Details of this work were reported in the Fourth and Fifth Quarterly Progress Reports. Calibration was performed first on the receiver with the antenna removed, using an attenuator and termination assembly in place of the antenna. Receiver input temperatures between 220K and 325K were generated by immersing the termination in liquid nitrogen and in water at various temperatures and adjusting the attenuator. The antenna was then replaced and the complete receiver directly calibrated by observing the temperature of a microwave absorber inside a specially prepared hot-cold environmental test chamber. Results of this new direct calibration experiment were excellent and verified that antenna transmission coefficients previously determined by less exacting methods were correct within approximately 1 percent.

A small difference in absolute temperature calibration -- slightly over 1 percent at worst point -- was found between the original brightness temperature calibration curve and the new calibration curve for 54.5 GHz. Relative calibration was changed by a much smaller amount. Errors of such magnitude, if they existed during field experiments with MK I, would be trivial since practically all data analysis was based on relative brightness temperature measurements over a rather small temperature range.

3.4 TRAINING MATERIAL AND ASSISTANCE

SMED prepared a 32-page booklet entitled "MK I THERMASONDE Training Material" in accordance with desired outline provided by personnel at NAPCA, Institute for Air Pollution Training, and delivered 50 copies to NAPCA for distribution. In addition, SMED prepared a half-day lecture on the theory and practice related to MK I THERMASONDE development and use and presented that lecture during the week of

June 9 to 13, 1969 as part of NAPCA's course entitled "Meteorological Instrumentation in Air Pollution." This course was given at NAPCA's facility in Research Triangle Park, North Carolina.

3.5 MK I SENSITIVITY IMPROVEMENT

By the fall of 1969, continued development effort at SMED on low noise mixer diodes and mixer structures had resulted in performance considerably better than that of the mixer installed in the MK I THERMASONDE some months earlier. At the request of the NAPCA Project Officer, Mr. Lemmons, SMED prepared a Task Description for MK I THERMASONDE Sensitivity Improvement outlining the work effort involved in, and expected results from, installation of a new mixer. A noise figure improvement of approximately 2.2 dB and a receiver sensitivity improvement of 1.6 were expected. This task was approved as Contract Modification No. 2 and the task completed in August 1970.

As reported in Quarterly Report No. 6, an actual improvement in mixer and system noise figure of approximately 2.5 dB was achieved and the minimum detectable temperature reduced from approximately 0.16°C for a 60-second integration time to approximately 0.09°C. Prior to installing the new mixer, system and mixer noise figures were approximately 14.0 dB and 10.6 dB, respectively; afterwards these were reduced to approximately 11.4 dB and 8.1 dB. During this work it was discovered that the local oscillator in the MK I was excessively noisy, thereby degrading measured noise figure by 1.5 dB compared to measurements with other local oscillators. Tests showed this noise to be characteristic of the particular klystron type being used and therefore impractical to eliminate without unduly extensive THERMASONDE modification. If this noise could have been eliminated, the mixer noise figure would have dropped even further to 6.6 dB.

MK II design will eliminate this problem.

The THERMASONDE Handbook of Instructions was revised and reissued to show the changes made necessary by modifications to the equipment for sensitivity improvement, and to include the new calibration curves generated earlier. In September 1970, field tests were conducted at SMED by NAPCA and Sperry Rand personnel and the THERMASONDE returned to NAPCA custody.

BLANK PAGE

4. DEVELOPMENT OF THE MK II THERMASONDE CONFIGURATION

4.1 INTRODUCTION

The concept and configuration of the MK II THERMASONDE underwent several significant changes since its inception in March 1970. The basis for much of the change was experience gained through continuing use of the MK I THERMASONDE and the successful demonstration of recent data reduction techniques.

The original concept called for MK II to be a sensitive, stable, fixed frequency, linear power receiver. Automatic gain control was to be incorporated to continuously stabilize the receiver gain, and a solid state noise source or hot load was to replace the gas noise tube used in the null balance system. New techniques for demodulation, chopper speed control, calibration, and general system improvement were to be investigated. Peripheral equipments such as x-y plotters and height function generators were to be evaluated. The THERMASONDE was to be a unitary system; i. e., the receiver pedestal, drive, recorder and controls were to be at the same location (see artist's concept, Figure 4-1).

During the First and Second Quarters of the contract period, investigations into the AGC produced changes in the receiver design. Use of a differentially controlled AGC signal in quadrature to the brightness signal removed the necessity that the chopper be temperature controlled to maintain accurate gain control. The data output would then be the direct difference between antenna brightness temperature and the chopper temperature. If antenna and chopper were maintained at local ambient temperature, the data output would be the change in brightness temperature with elevation angle. The differential temperature was desirable from the standpoint of output accuracy.

The Third Quarter of the contract saw the system concept evolve into a remotely operated unit (see artist's concept, Figure 4-2). The elimination of null balance operation removed the need for on-site operator supervision and made the MK II amenable to remote control operation.

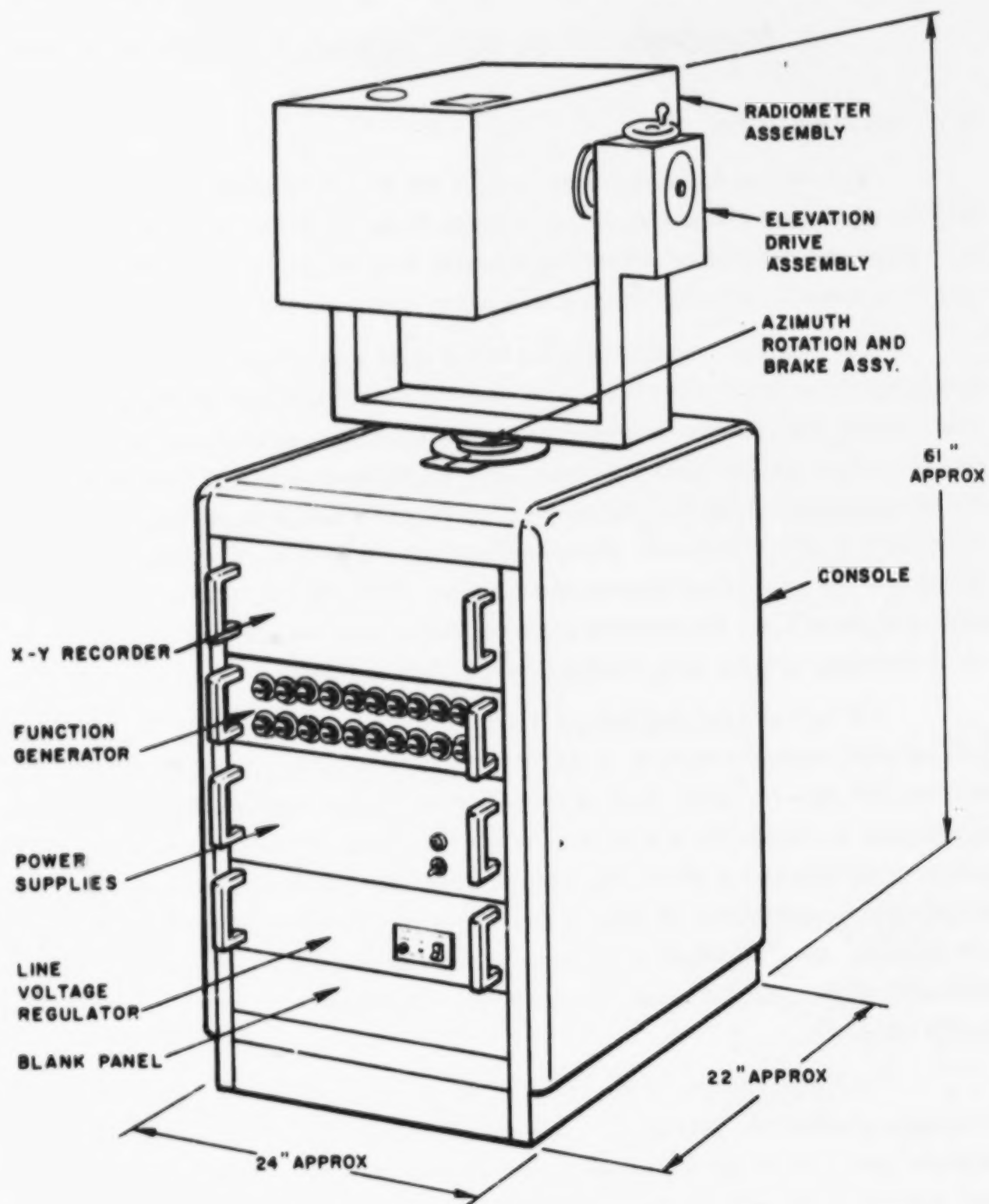


Figure 4-1. MK II THERMASONDE, Unitary System

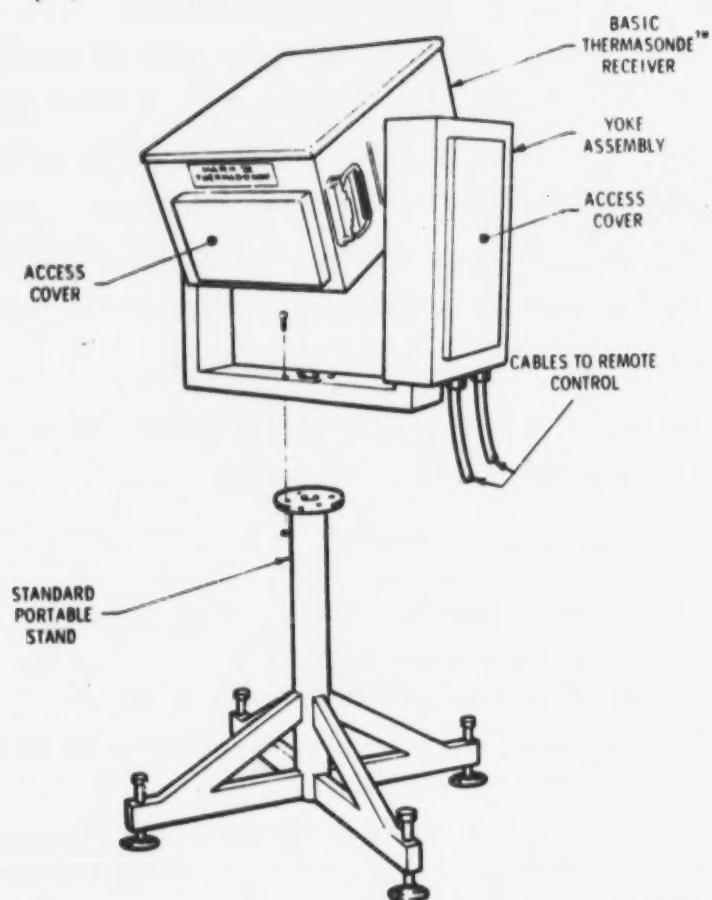


Figure 4-2A. MK II THERMASONDE Outdoor Unit

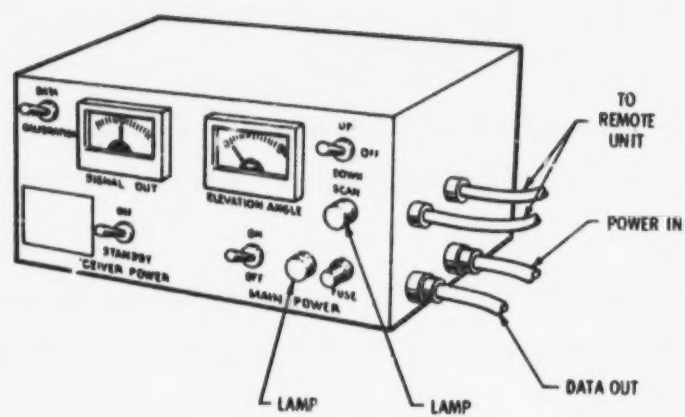


Figure 4-2B. MK II THERMASONDE Control Unit

All necessary output data and elevation controls would be located in the remote control package. The pedestal and yoke assembly became similar in configuration to the MK I except for remote control provisions. The receiver was also similar in appearance to the MK I receiver. Further investigations into data reduction methods produced a need for a versatile, more elaborate elevation scan to facilitate the data reduction techniques. Optional analog or digital output of data were also reviewed. A more reliable calibration method was also suggested, in view of the revised receiver design.

In April of 1970, during the Fourth Quarter, a conference with NAPCA and SRRC personnel was held at SMED in Clearwater. The purpose of this meeting was in part to further refine the requirements for MK II.

The result of this conference was:

- MK II would definitely be remotely controlled;
- A precision 60 Hz supply would be included for the chopper to permit operation from power sources of unstable frequency;
- A height function generator plus barometric correction would be part of the basic configuration;
- A versatile elevation drive would be included to provide slew, low speed continuous scans and incremental step and dwell operation in both directions;
- Null balance was eliminated in favor of quadrature AGC;
- A new low noise, low loss antenna would be used;
- New lower noise figure mixer would be provided;
- Measurement of absolute temperature rather than differential measurements would be provided to accommodate certain data translation techniques.

As a result, the THERMASONDE output was to be corrected to give absolute temperature rather than the differential output previously discussed, and new calibration procedures would be required.

In July 1970, during the Fifth Quarter, meetings were held with SRRC personnel at SMED in Clearwater to discuss the MK II development. The meetings resulted in the following conclusions:

- Data translation techniques under development by NOAA-WPL and SRRC required measurement of atmospheric brightness temperature to an accuracy of $\pm 0.5^{\circ}\text{C}$ rss,
- Frequency error was to be held to ± 10 MHz or less,
- RF bandwidth was to be less than 500 MHz if possible, and
- Output was to be in degrees Centigrade.

The absolute accuracy of 0.5°C and the tight frequency stability required careful reconsideration of various sources of measurement errors.

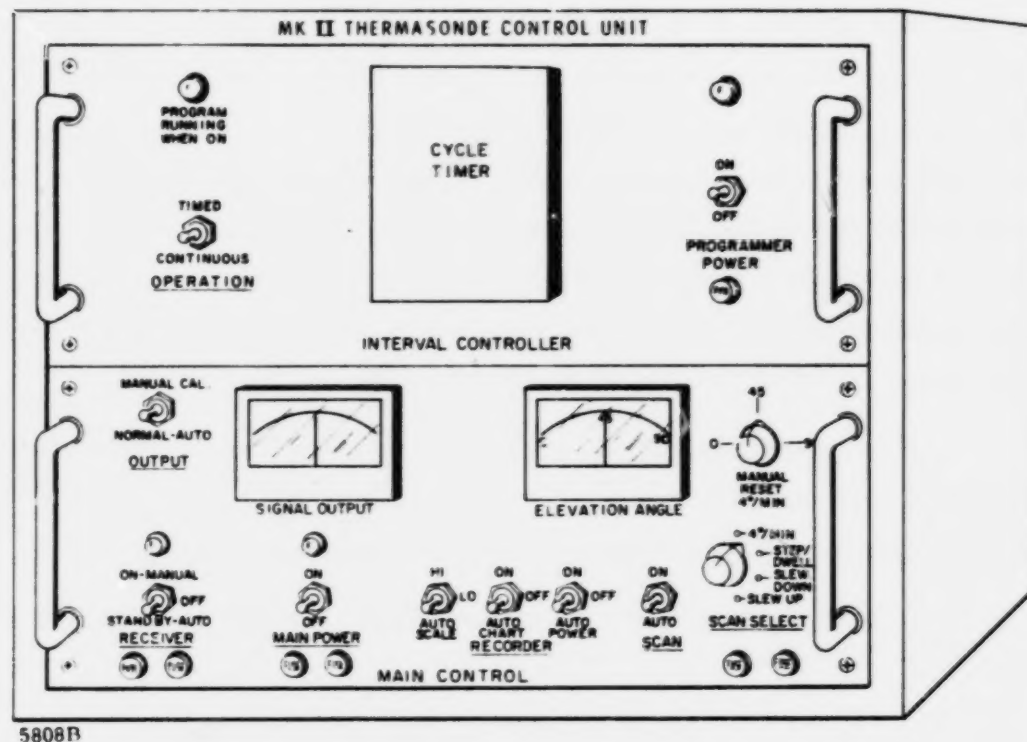
Meetings, during the Sixth Quarter, were held with personnel at NOAA-WPL in Boulder, Colorado, and with weather bureau personnel at St. Louis, Missouri. The purpose of the trip to NOAA-WPL was to ascertain the status of THERMASONDE data reduction techniques being investigated there. The purpose of the St. Louis visit was to observe weather bureau personnel using the MK I THERMASONDE and the SRRC overlay look-up data reduction technique. As a result of this trip, both SRRC and NOAA reduction techniques were considered reasonable and the MK II would be designed to accommodate both. Basically, this resulted in a more sophisticated elevation drive mechanism for the THERMASONDE, since the two approaches incorporate very different scan modes.

In the Seventh Quarter, a meeting was held between NOAA, APCO, SRRC and SMED personnel at Raleigh, North Carolina to discuss THERMASONDE development. The conclusions of this conference effecting MK II were:

- Both a priori and look-up techniques are suitable translation methods;
- MK II should be as automated as possible;
- Analog and digital output were desired;
- Automatic re-zero of elevation drive would be provided in addition to other features of the elevation drive mechanism;
- Consideration was to be given to field changeable local oscillator frequency;
- Height function generator was no longer required with new data translation techniques.

The present MK II concept is basically a sensitive, linear power receiver, with an absolute measurement accuracy of $\pm 0.5^{\circ}\text{C}$ rss, automatic gain control, remote operation, a versatile elevation drive for data translation techniques, and automated control. Further options to be considered are digital outputs, variable frequency operation, and functional processing of data outputs.

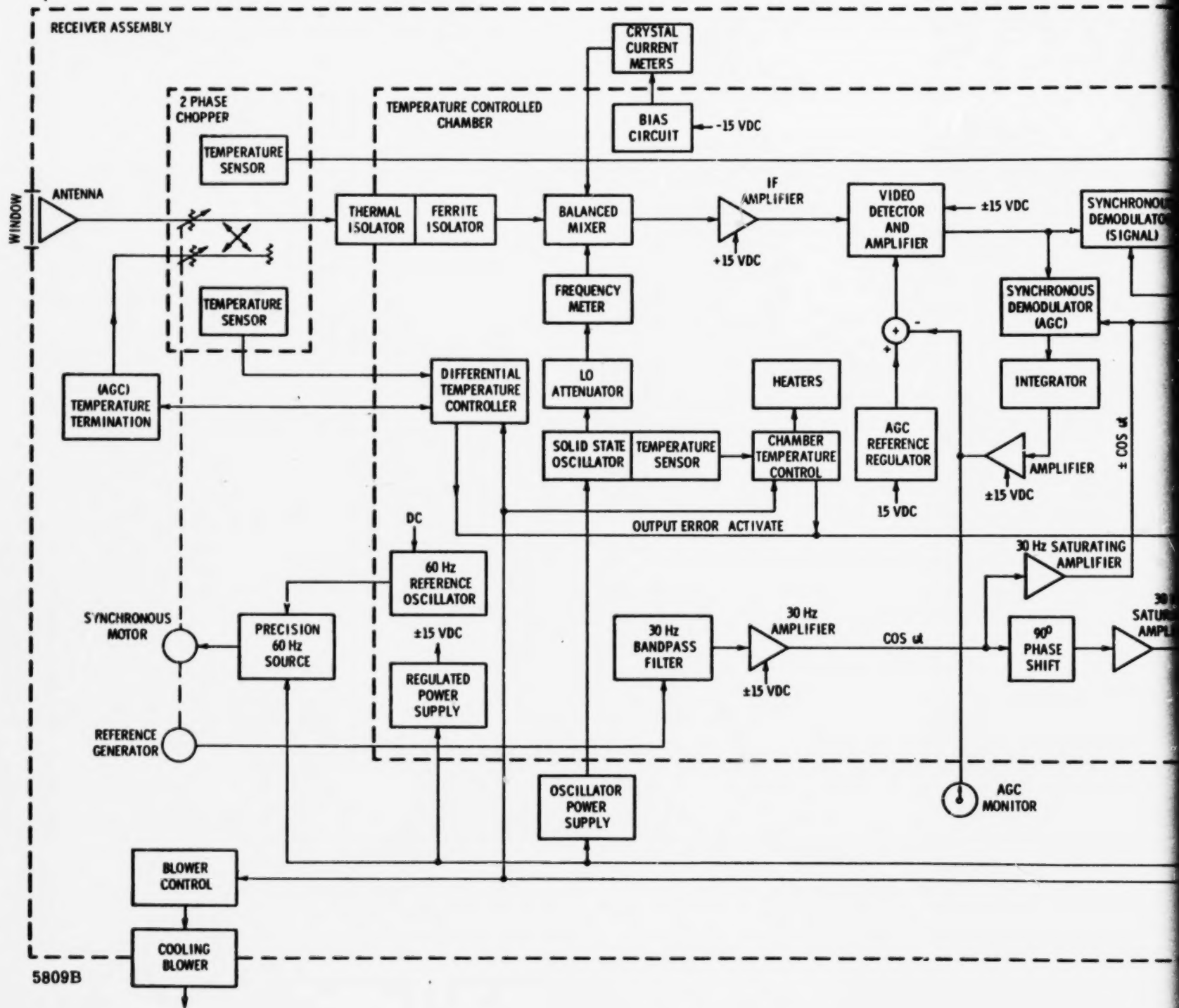
An artist's concept of the control unit configuration needed to provide the functions established at the last conference is shown in Figure 4-3. A basic block diagram of the latest configuration is shown in Figure 4-4.



5808B

Figure 4-3. MK II THERMASONDE Control Unit

A



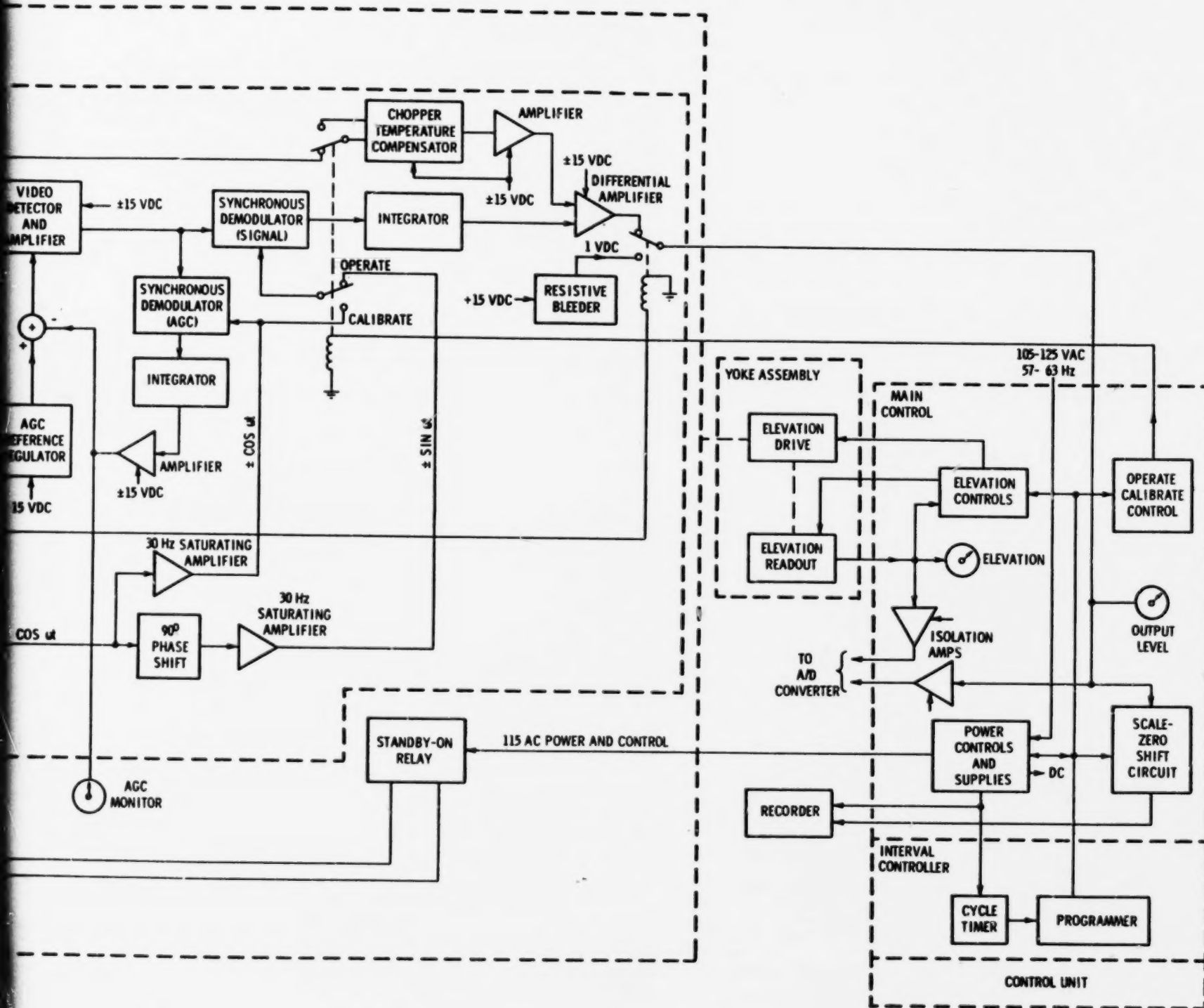


Figure 4-4. MK II THERMASONDE,
Basic Block Diagram

4.2 ADVANCED DESIGN REQUIREMENTS INVESTIGATION

Prior to the actual design of the MK II THERMASONDE, investigations into the various equipment areas was begun. The electrical design investigation concentrated heavily on circuits, techniques and components which would yield a MK II unit with improved performance and reduced cost.

4.2.1 Automatic Gain Control

Theoretical investigations of SMED's quadrature automatic gain control (AGC)* were conducted to determine the most critical parameters as applied to the MK II system. Appendix A contains a summary of that work in some detail.

In a gain controlled amplifier, the compression ratio is a measure of its ability to compress changes in output signal. A 1 dB change in receiver gain can be compressed to 0.01 dB with a compression ratio of 100. The performance of MK I and MK 0 indicated that a compression ratio of 50 would be adequate to keep fluctuations below 0.01 dB. This range of C. R. is obtainable in presently available integrated circuit form.

In the AGC receiver, a reference temperature is injected into the signal channel in quadrature to the brightness temperature as the AGC signal. The reference is then recovered by synchronous quadrature demodulation and compared to a standard. Any difference between the reference and standard results in correction of the receiver gain to its calibrated value.

A breadboard of the AGC for MK II was constructed and tested using the MK 0 as the receiver. The results of the tests showed excellent agreement with the system equations developed. The data was tabulated in Monthly Report No. 5 and is part of Appendix A.

During the period of this contract, SMED constructed a 35 GHz receiver (for another program) which incorporated automatic gain control. The system is essentially the one considered for MK II and has performed superbly in all field measurements to date.

* Sperry proprietary technique. Patent applied for.

4.2.2 Demodulator

A reed switch demodulator was investigated as a replacement for the more expensive solid state demodulators used in MK I. Tests finally showed that maintenance of critical phase relationships required for operation of the AGC probably could not be maintained using reed switches. This conclusion is drawn partly from operation of the MK 0 THERMASONDE which employs a reed switch demodulator but not AGC. Satisfactory operation was achieved after some difficulty, but precise phase control is not required or maintained in that unit.

4.2.3 X-Y Recorder

Investigation and tests were carried out on numerous X-Y recorders to determine their suitability under external environmental conditions appropriate to the unitary equipment concept. During the contract period the concept of the unit changed from outdoor unity to a remote controlled receiver with recorder in protected environment. Later, the elimination of the height function generator also eliminated any requirement for servo drive on the recorder elevation axis so that a time base, strip type recorder could be used. In the final analysis, an industrial type or lab type strip recorder will be quite sufficient and more economical.

4.2.4 Source Temperature Computer

Investigation into correction of the data for antenna temperature changes was carried out in conjunction with the preliminary design. As the system design progressed, a differential signal (between chopper and brightness) output was determined to be the data output. The antenna and chopper temperature were not controlled except to local ambient. When the requirement for absolute temperature measurements was established, the chopper temperature computer was added to correct the output to absolute temperature in degrees Centigrade. Hence, the source computer has evolved into the chopper temperature computer for MK II.

4.2.5 Video Tracking Filter and Chopper Drive

Design investigations were conducted into several types of bandpass tracking filters which could track the power line frequency and eliminate the need for a precision drive source. However, the preliminary design analysis of the effect of phasing errors

in the AGC indicated that extremely tight phase control was necessary. It would be quite expensive, if at all possible, to maintain such a stable phase shift in the bandpass of the filter. Hence, a precision 60 Hertz power source is considered necessary for MK II.

4.2.6 Height Function Generator

Considerable time was spent in conjunction with SRRC in development of the automatic height function generator. The generator was to provide an applicable height function curve, corrected for changes in atmospheric pressure to provide a real time readout of temperature versus height. The design of the generator was completed and breadboarded. The results were very good and the device was assembled and attached to the MK 0 for testing.

During the progress of the contract, the data reduction techniques of SRRC and NOAA-WPL developed in directions which made it undesirable to use the height function generator in the data reduction. The design, however, is available should future use of a height function generator be required.

4.2.7 Solid State Local Oscillator

A survey was made for possible vendors who could provide a solid state local oscillator. The complication of excess noise content in the MK I local oscillator placed additional requirements on the LO in addition to the necessity of maintaining tight frequency control. A Gunn oscillator is available which apparently meets all requirements. A similar Gunn oscillator, operating at 35 GHz, has been used by SMED in a radiometer receiver with excellent results.

4.2.8 Antenna Design Requirements

The MK I and MK 0 THERMASONDES employed a shrouded, J-feed, 6-inch diameter paraboloidal antenna of relatively conventional design having a beamwidth of approximately 2.5° in both planes. Total effective loss for that antenna, including feed line loss and effective spillover losses, was approximately 0.9 dB.

As a result of analyses of data translation techniques, it was concluded that a 2.5° elevation beamwidth caused excessive data smearing while a wider beamwidth in azimuth would be of no consequence. A larger antenna aperture in elevation was called for; to keep the antenna compact, a smaller aperture could be used in azimuth. Beamwidths of approximately 1.3° in elevation by 6° in azimuth, corresponding to a reasonable size aperture of about 12 x 2 inches, were settled upon. An entirely new antenna design was, therefore, needed. This new antenna should have not only the desired beamwidths, but to improve overall sensitivity, should have the lowest possible losses, and to improve measurement accuracy, the lowest possible sidelobe radiation. It must be noted that the measurement of brightness temperature at a given angle can be accurate only to the extent that the radiation into the antenna represents the temperature at that angle. Radiation entering the antenna from side and back lobes (from other angles) creates measurement errors of a kind nearly impossible to eliminate by any kind of calibration. Low side and back lobes are therefore essential to measurement accuracy.

Antenna design work during this program, based on these requirements, is described in Section 4.3.4.2 of this report.

4.3 PRELIMINARY DESIGN

4.3.1 Introduction

This phase of the program was to provide a preliminary design for the MK II THERMASONDE; and to generate candidate configurations, designs, specifications, prepare parts lists, schematics and drawings in advance of final decisions as to overall MK II configurations. In the face of maturing data translation techniques and revised operational requirements, several configuration revisions were made during this program, even during the last quarter, as outlined earlier in Section 4. These revisions have led to the present configuration which has sufficient accuracy and versatility to meet several data translation technique requirements, which is practical to fabricate and maintain and which places minimum burden on operating air pollution personnel. In other words, it is a nearly optimum configuration. Because of the lateness of some revisions, not all of the preliminary design was completed to the extent expected. This is particularly true in the areas of overall packaging and in the design of the elevation drive mechanisms and control unit; however, these are not critical design problem areas. Analysis and design of the truly critical parts of the THERMASONDE are about as complete as they can be without actual breadboard fabrication, test, and development.

4.3.2 Specifications

The specifications as they have developed are provided here. Some of the specifications are tentative as noted in each case. Environmental specifications remain as stated in section 2.3.2. Electrical and Functional Specifications for the MK II THERMASONDE are as follows:

The operating frequency shall be fixed at 54.5 or 55.0 GHz. There is a residual question as to whether frequency should be field changeable to permit operating the same unit at widely different altitudes or whether it should be fixed at the factory for best stability.

The radio frequency bandwidth shall be 500 MHz maximum. Because of the nonlinearity of the absorption versus frequency curve for oxygen, a narrower bandwidth is desirable; therefore, a design goal of 300 MHz has been established.

The IF bandwidth shall be at least 100 MHz. (This minimum bandwidth is needed to provide necessary temperature sensitivity.)

The temperature sensitivity shall be a maximum of 0.09 K when the integration time is 60 seconds. As a design goal, this shall be reduced to 0.05 K without increasing rf bandwidth.

The antenna beamwidths shall be approximately 1.3 degrees in elevation and 6.0 degrees in azimuth. The antenna design shall be such as to reduce internal losses to a minimum and to control or suppress radiation outside the main lobe.

The brightness temperature outputs shall be a voltage linearly proportional to temperature in degrees C with fixed scale factor and fixed recorder chart scale deflection per degree. Arrangements shall be made so that the operator may select either the actual brightness temperature at any angle or the difference between the brightness temperature at 0 degree elevation and the temperature at other angles. In either case, the design goal overall accuracy shall be ± 0.5 degree C rss.

The elevation angle readout shall provide an accurate indication in voltage increment per degree of antenna pointing angle. The design goal accuracy shall be $\pm 0.2^\circ$ rss.

The elevation drive mechanism (through the control unit) shall provide the following elevation drive modes from 0 to 90 degrees elevation:

- Slew at a rate of 180 degrees/minute, minimum in either direction
- Continuous scan up at a rate of 4 degrees/minute
- Automatic stepped scan up with 2-minute dwell at each step and slew between steps, with up to 15 steps, with the size of each step controlled by a plug-in program card.

When in programmed operation, the antenna will be automatically slewed to 0 degree elevation at the completion of a sounding.

The Control Unit (exclusive of recorder) shall provide for both manual and automatic control of the THERMASONDE. Controls and indicators tentatively include:

- Control of power applied to all units,
- Test of THERMASONDE operational readiness,
- Selection, activation and override, when desired, of elevation scan modes and other operations,
- Indicators of all control functions as well as present elevation angle and brightness temperature, and
- All necessary controls for setting up and activating the interval programmer which will automatically take unattended soundings as required.

4.3.3 System Configuration

The MK II THERMASONDE configuration consists of an outdoor unit comprised of the receiver, support yoke and pedestal, and indoor components which are the control unit and recorder. The design includes cables up to 100 feet long so that the controls may be placed in an office or laboratory while the outdoor unit is located on the roof or away from the building.

4.3.3.1 Outdoor Units

The MK II receiver, as shown in the block diagram, Figure 4-4, is basically a Dicke-type radiometer operating as a linear (difference) power receiver. In order to meet necessary requirements of long term scale factor (gain) stability and temperature measurement accuracy under specified variations in environmental conditions, certain refinements were devised, including -

- Continuous automatic gain control,
- Temperature control of all critical circuits,
- Analog computer correction for variations in antenna and chopper (modulator) temperature,
- Means for remote test of receiver accuracy, and
- Means for remote indication of faulty operation.

Automatic gain control is provided in the following way:

- A matched waveguide termination, which acts as a broadband signal source, is precisely maintained at a temperature approximately 200°C above the chopper temperature by a differential temperature controller.
- The output of the termination is chopped by the AGC portion of the chopper giving rise to a 30 Hz modulated microwave signal of precisely stable peak-to-peak amplitude of approximately 200°C.
- This modulated signal is coupled into the signal line through a directional coupler of about 13 dB coupling factor. Through coupling, the amplitude is reduced to approximately 10°C peak-to-peak. At the input to the receiver, the AGC signal and the chopped signal from the antenna are both present, but modulated in phase quadrature.
- The composite signal is then processed through the receiver in a normal manner up to the synchronous demodulators. At the demodulators, the AGC and antenna signals are separated by quadrature demodulation.
- The AGC signal is then processed and fed back to control overall gain by directly controlling the gain of the video amplifier.

While experience with the MK I has shown that the gain variations to be expected without AGC are relatively small when the circuit temperatures are well controlled, it is believed that the long term gain stability demanded of MK II can only be achieved with AGC.

For various reasons, control of the antenna structure and chopper temperature to the accuracy demanded was not considered practical and means of correcting the output for changes in antenna and chopper temperature had to be provided. The solution is a linear temperature sensor operating through a simple analog computer circuit (chopper temperature compensator and difference amplifier) which not only corrects the output for changes in chopper temperature but also permits a bipolar output reading which has a zero at 0°C.

The remote test of receiver accuracy (calibration) is accomplished through a relay which changes the reference phase into the signal demodulator causing the AGC level to appear in the receiver output. At the same time, a fixed resistance is switched in place of the chopper temperature sensor which causes its output to become zero. If everything is working properly, a fixed, known level will be observed on the control unit indicator; otherwise, the level will be wrong. If a fault occurs in temperature control of the AGC termination or the local oscillator which would produce a gain or frequency error, a relay will be activated producing a fixed output fault indication from the receiver.

The receiver is supported at its center of gravity by a pedestal assembly which consists of a portable stand and a yoke assembly. The yoke includes the elevation drive mechanism and elevation readout. The drive mechanism provides for scanning the receiver (with included antenna) from 0° to 90° and slewing back to 0° in the ways previously described.

4.3.3.2 Indoor Components

The control unit necessarily controls all THERMASONDE operations. Provisions are made in the control unit so that soundings may either be made or initiated manually, by an operator, or initiated automatically by a timer and made by a programmer.

The remote operation, and particularly automatic operation, make it essential that the equipment be not only highly reliable, but that it include automatic self-monitors and fault indicators. Further, any fault which existed at the time of an automatic sounding must be recorded in some fashion so that erroneous data may be discarded. The present plan is to provide a fixed voltage level output as a fault indicator. This voltage will provide a noiseless, full scale deflection on a recorder chart which cannot be mistaken for a true sounding.

The control unit has two basic subassemblies: the main control unit and an interval controller.

The main control, as required by the specifications, provides all manual control as previously described. The interval controller is the equivalent of a robot operator. It includes a repeat cycle timer which may be set to activate a programmer at any desired times of day over a 24-hour period and to repeat day after day. It also includes an electromechanical programmer set up to activate all THERMASONDE controls in the proper time sequence to take soundings automatically when activated by the timer. The interval controller is a recent addition to the MK II THERMASONDE configuration to reduce the demand for operator time, a particularly important consideration for night and weekend operations.

4.3.4 Design Details

4.3.4.1 Error Budget

An extensive analysis was conducted to establish the sources and magnitudes of errors for the MK II system. During the course of the preliminary design, as a more detailed understanding of the various system errors was developed, the error budget was modified and some errors redistributed. The present error budget is:

	<u>Error °C</u>
Frequency of Operation	0.056
Beam Pointing Accuracy	0.080
RMS Receiver Noise	0.090
Recorder Accuracy	0.050
Chopper Temperature Computer	0.08
AGC Source Control	0.02
AGC Compression	0.08
DC Output Drift	0.015
Calibration Error	0.20
Signal-AGC Phasing Errors	0.42

The root sum square of these errors is $\pm 0.5^{\circ}\text{C}$. A detailed analysis of the errors is located in Appendix B. The error budget given is a present best estimate. It will be subject to modification during development when the relative difficulty of sustaining accuracy in one area relative to another is determined. The error budget will be continually reviewed to insure that no errors are overlooked at any time and that the rss value does not exceed $\pm 0.5^{\circ}\text{C}$.

4.3.4.2 Antenna

The original plan for MK II was to use the same antenna assembly as in the MK I. The basic contract did not include any provision for investigating a new antenna configuration. In April of 1970, just prior to expiration of the originally contracted phases, it was jointly decided between NAPCA and Sperry Rand that the MK II should have a new and improved antenna. Some work was done on that antenna as reported in the Fourth Quarterly Progress Report (May 1970) and this item was included in SMED's revised proposal for the Preliminary Design Phase (IIIA), also in May.

At that time, calculations had indicated that a lens-corrected sectorial horn antenna with an aperture of approximately 2 x 12 inches would produce the desired beamwidths with a minimum of outboard radiation and with minimum dielectric losses. Computed dielectric losses for a 2 x 12 inch stepped cylindrical lens were under 0.2 dB. This loss did not include any allowance for mismatch loss at the lens surfaces. Surface matching was known to be required and probably difficult and expensive. Further calculations indicated that even with fairly good surface matching, the total lens loss would still be considerably higher than the minimum believed possible for an antenna of this aperture in the 55 GHz frequency range. Some lens antenna parts were made and tested for match; indications of reasonably good match were provided but losses were still higher than hoped for.

Means were then sought to reduce these losses. One of the means first considered was a much smaller lens in a small feedhorn to illuminate a hog horn antenna. The greatly reduced lens size and thickness would naturally result in lower dielectric losses; however, the surface matching problems remained. Various means of eliminating the matching problem were considered, such as making the lens of a relatively thick section of polystyrene foam having a dielectric constant not much different than air so that no matching would be needed. Unfortunately, the curvature of this lens was so radical that total reflection would occur over part of its width. Means were then considered to eliminate the lens entirely.

A configuration was devised in which a 12 x 2-1/2 inch aperture hog horn is illuminated by a 2-1/2 inch long hog horn. (In the small hog horn, a parabolic sector is adequately approximated by a circular section which is easy to fabricate.) The preliminary design of this antenna is complete. No tests have been made of the design; however, it is estimated that total internal losses in the antenna (including feedline) will not exceed 0.2 dB, and the radiation lobe structure should be very good.

4.3.4.3 Chopper and Speed Control

The microwave chopper will be a 2-phase 30 cycle modulator driven by an 1800 rpm synchronous motor. The chopper will consist of two rotating mica discs inside a heavy aluminum enclosure. The discs run in slots in parallel waveguide sections. Each disc is constructed so as to produce a 30-Hz square wave modulation in its respective waveguide channel. The two discs are aligned so that they are positioned mechanically $90^\circ \pm 0.1^\circ$ out of phase with each other. Hence, the modulation in the two microwave channels is in quadrature (90° out of phase). Required coupling between channels is provided by coupling holes in the common waveguide wall.

Precision, sealed, ball bearings are used to reduce any axial or radial play in the mountings. The heavy enclosure prevents sudden changes or fluctuations in the chopper temperature. Two platinum sensors are imbedded in the chopper housing to provide precise temperature sensing to the chopper temperature computer and to the AGC differential temperature controller. Careful consideration has been given to mechanical design so as to facilitate assembly and construction of the chopper and waveguide assemblies.

Preliminary investigations and analysis found a bandpass tracking filter was impractical. The chopper, therefore, must run at a precise speed to generate a precise frequency. A precision 60-Hz oscillator has been selected which has a stability of 0.005 percent (commercial power line frequency regulation is 0.03 percent). A simple power amplifier will be used to supply the drive power to the chopper drive motor. The oscillator will be enclosed in the temperature controlled electronics section to maintain the best possible stability.

4.3.4.4 AGC Source and Controller

The AGC temperature source will consist of a temperature-controlled load mounted in stainless steel waveguide. The termination will be heated to $200^{\circ}\text{C} \pm 5^{\circ}\text{C}$ above the temperature of the chopper. This temperature differential will be maintained within 0.2°C for all values of chopper temperature between -35°C and $+50^{\circ}\text{C}$. The differential controller will also have a dynamic accuracy of 0.2°C , i.e., the controller will maintain accuracy while tracking changes in the chopper temperature on the order of 2°C per minute.

The waveguide and load are mounted in a brass block in which a cartridge heater and platinum sensor are imbedded, and this entire assembly is housed in a 2-1/2 inch diameter insulated case. This construction is designed to minimize heat flow out of the load. The average power required after warmup will be less than 10 watts.

The differential temperature controller is designed especially for the purpose of precise temperature control of the load. Pure metal platinum sensors are used because of their linearity and their matched characteristics over the 200°C differential range. The two sensors must track resistively while the chopper sensor changes over the -35 to $+50^{\circ}\text{C}$ ambient and the AGC termination sensor changes from $+165$ to $+250^{\circ}\text{C}$. The two sensors comprise legs of a Wheatstone bridge which are balanced when the two sensors are at temperature differentials of 200°C . The unbalance of the bridge is amplified and used to drive the input to a zero voltage switch. A time proportioning ramp signal is summed with the bridge signal so that under steady state conditions, the time average power to the AGC heater will be constant. This method reduces the cycling and temperature fluctuations of the AGC load. The termination is also protected against sensor failure by a fault sensing circuit in the controller and a sensor on the termination. The zero voltage switch eliminates any RFI due to switching transients.

In the analysis of the AGC controller, it was found that even pure platinum does not have a sufficiently linear R-T curve to permit both sensors to have the same 0°C resistance in this application. In order that both have the same rate of change of resistance with temperature when operating at a differential of 200°C , the sensor operating at the higher temperature must have a slightly higher basic resistance.

4.3.4.5 Receiver Front End

The MK II receiver front end, which includes all microwave circuitry except the antenna, is radically different from the MK I. Provisions in the MK I for nullpoint checking and controlled noise injection to balance in order to get accurate measurements have been completely eliminated from the MK II. Instead, provisions are made in the MK II for automatic gain control and self-checking to ensure measurement accuracy. These changes have resulted in elimination of several major components needed in MK I: the expensive precision attenuator and gas noise tube, the large noise tube power supply and firing circuit, a microwave switch and several smaller components. In place of these parts, a hot termination AGC source with precision differential temperature controller have been added, the chopper changed to two-phase and the coupler included, and some complications added to the electronics section.

In the microwave receiver proper, which includes the balanced mixer and local oscillator chain and the IF amplifiers, some important design changes have been made. The mixer proper will be electrically at least equal to that retrofitted into the MK I in 1970, but will be improved mechanically.

It is planned to use the same frequency meter and LO attenuator in MK II as was used in the MK I; however, the local oscillator itself will be changed from a klystron to a Gunn diode oscillator. This latter change has a considerable impact upon overall receiver design.

- Power consumed by the diode is much less than a klystron and its power supply is much simpler, smaller, lighter and consumes much less power.
- LO noise will be reduced, providing lower noise figure and better overall sensitivity.
- Initial diode oscillator cost is about twice that of a klystron; but, because diode life should be many times greater, cost per unit operating time should drop appreciably.
- Since the diode consumes little power itself, it will be easier to temperature control and thus more easily frequency stabilized.
- Removal of the klystron (along with the gas noise tube) eliminates the last of the thermionic tube devices from the equipment.

A survey was made of available state-of-the-art intermediate frequency amplifiers for the MK II receiver. Suitable amplifiers are now available from several manufacturers. State-of-the-art noise figure for production units is a maximum noise figure of 2.5 dB in the 100 to 200 MHz band and a typical noise figure of 2.0 dB over that band. No real improvement over the MK I IF amplifier is indicated at this time. Final selection of IF amplifier for MK II is deferred until later to take advantage of any further improvements which may occur.

4.3.4.6 Post IF Electronics

The electronics section of the MK II will contain several new concepts in signal handling which have not yet been tested in field units. The analysis of errors in the electronics has dictated that extreme care must be taken to minimize variations in phase shift. High grade integrated circuit operational amplifiers with low drift and high stability are used for all amplification beyond the input stage. Precision passive components with minimum temperature coefficients have been selected to minimize phase shift variations in the signal/AGC channels. To further increase the overall stability, the entire electronics section will be closely temperature controlled.

The video detector is similar to that of the MK I. It will consist of a broadband matching transformer and two 1N830A diodes in a voltage doubling arrangement. The voltage response should be approximately 10 millivolts per microwatt of power input.

The input stage will be a low noise preamp -- a single low noise FET designed especially for low noise and small signal operation.

The amplifier stages between the preamp and the gain controlled amplifier will have a voltage gain of 100,000 to 150,000 which is variable via a pot in the first amplifier stage.

Special consideration has been given to the 30 Hz bandpass filter located in the video amplifiers ahead of the AGC stage. Analysis of AGC error due to phase shift beyond the chopper shows a phase shift of less than ± 0.5 electrical degrees is mandatory for a satisfactory AGC channel. Active bandpass filters are the most practical

at this frequency from the standpoint of component size and insertion loss. However, phase instabilities have been noted in some of these devices which are excessive for MK II applications. Passive filters can be used to provide a stable phase response but at the expense of less than unity gain and bulkier components. During breadboard testing, a further investigation of the active filter is planned.

The automatic gain control stage incorporates an integrated-circuit gain-controlled amplifier. The amplifier has a compression ratio of 66 and a dynamic range of 80 dB. An extremely stable AGC reference standard must be used since any variation in this source has the same effect as a receiver gain change. The gain control voltage changes the gain at a rate of approximately 140 dB per volt. A source with adequate stability has been chosen, and will be included in the temperature controlled section of the radiometer.

To minimize crosstalk between signal and AGC references, stringent demands have been placed upon the demodulator switch timing. The switching must occur within 0.1 electrical degree of chopper switching and within 0.1 electrical degree of quadrature between channels. Otherwise, excessive crosstalk appears in the AGC channel causing undesired changes in receiver gain. Special chopper type N-channel MOSFETS have been selected for use as chopper switches.

The quadrature demodulation signal will be generated by an ac generator coupled to the chopper shaft. This signal will pass through a 30-Hz bandpass filter identical to the video bandpass filter. Any change in temperature which causes a phase shift to the video signal will cause an equal phase shift in reference signal, preventing differential phase shift error. After filtering, the sine wave generator signal is converted to a square wave and applied to the chopper gate as the demodulation waveform. A transistorized phase shift network has been designed for producing the quadrature signal from the generator, and again care has been taken to ensure extremely good stability.

The output of each demodulator is fed into an integrator similar to those in MK 0 and MK I. A very stable preamp/amp is used to ensure good dc amplification at minimum drift and offset, since any change which occurs beyond the signal demodulators cannot be corrected by the AGC. The AGC integrator amplifier must have the same high quality since any change in the amplifier gain appears as a receiver gain error. This AGC signal is then compared to the reference and the error used to correct the receiver gain.

The chopper temperature computer is used to correct the output differential temperature so that it is referenced to zero degrees Centigrade. The computer is basically a precision current source supplying current to a platinum sensor. Chopper temperature changes produce voltage changes in the same proportions as would antenna brightness temperature changes which are then added to the receiver output. Again, good dc amplification and stability are provided by a preamp/amp dc amplifier, and good linearity is produced by the platinum sensor.

The high gain of the receiver stages requires the decoupling of all amplifier stages to reduce chances of oscillation, and the careful layout of various stages to reduce pickup or crosstalk. The electronics will be assembled on printed circuit boards and all necessary adjustments and test points will be accessible through the cover of the temperature controlled section without disrupting the controlled environment.

4.3.4.7 Pedestal Assembly

The pedestal assembly for the MK II will be of construction similar to the MK I. It will consist of a rigid U-shaped yoke constructed of rectangular tubing, which is mounted on a tubular stand.

The yoke should be somewhat shorter than for MK I due to the configuration of the MK II receiver. The receiver will mount between the arms of the yoke such that the supports for the receiver are acting through the center of gravity of the receiver package. The supports are short sections of shaft mounted in sealed ball bearings. This reduces the load requirements on the elevation drive. The yoke will be aligned to antenna boresight and leveling indicator included.

The elevation drive will be mounted on the outside of the yoke assembly in a separate weatherproof housing.

The elevation drive unit includes the gearing, drive motor, feedback and position sensing devices associated with the drive end of the elevation servo system which includes portions of the control unit. Design of this unit is not complete, but it appears that a gear-shift mechanism will be required in order to accommodate the 45:1 speed difference required in changing from 4°/minute to 180°/minute. This speed range is

too great to be handled by a simple servo system alone. For this application, a simple position servo appears to be adequate; the low speeds involved should make rate feedback unnecessary.

The pedestal base or stand will be essentially the same as that provided with the MK I as shown in Figure 4-2. Four adjustable feet provide for leveling the receiver on uneven surfaces and the yoke and receiver can be rotated in azimuth on the stand.

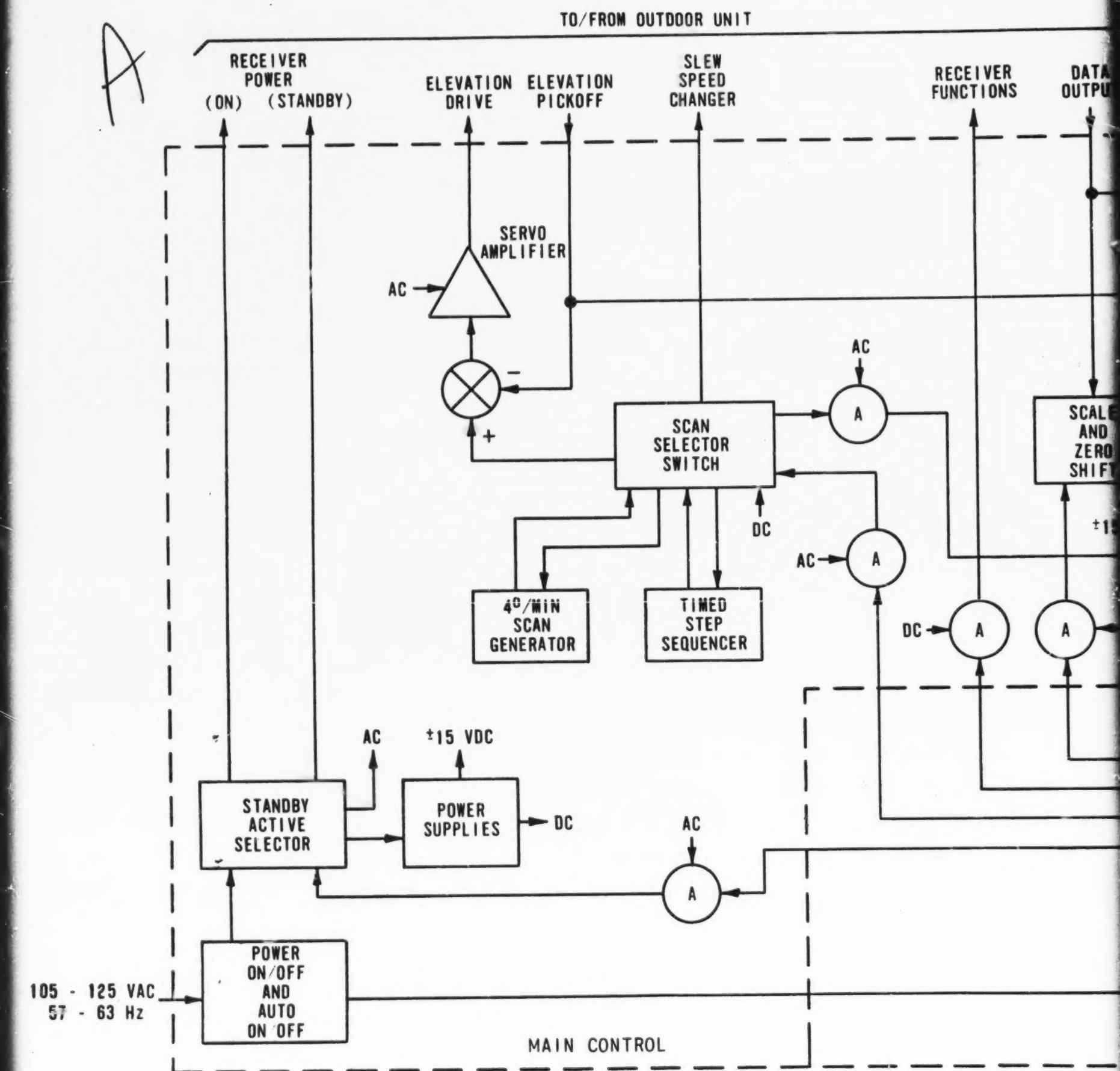
4.3.4.8 Control Unit and Recorder

The present concept of the MK II control unit provides for versatile elevation drive, receiver control and complete automation, yet does not require special operator skills or training. The control unit is composed of a main control assembly and an interval controller as shown in Figure 4-3. Figure 4-5 is a block diagram of the overall unit.

The main control assembly allows manual control of the receiver and elevation drive. The operator will control power to the receiver, check the operational readiness of the receiver, select the desired mode of scan, and begin or inhibit the scan or data output as desired. The main control is flexible enough that practically any desired type operation may be performed by the operator.

The elevation drive has not been completely designed due to very recent changes in requirements. However, an ac servo-type elevation drive seems well suited to the diverse scan modes and position accuracy requirements. This system provides versatility in the step and dwell mode or whatever nonlinear modes may be required. The scan modes available are a 180° per minute slew, a 4° per minute scan and a step and dwell sequence.

The scan and slew elevation drive signals will be essentially closed-loop position signals. The step and dwell scan will be generated by the program established on the stepping sequencer contained in the control unit. This program can be altered to provide variable angular steps and various numbers of steps and dwell times.



B

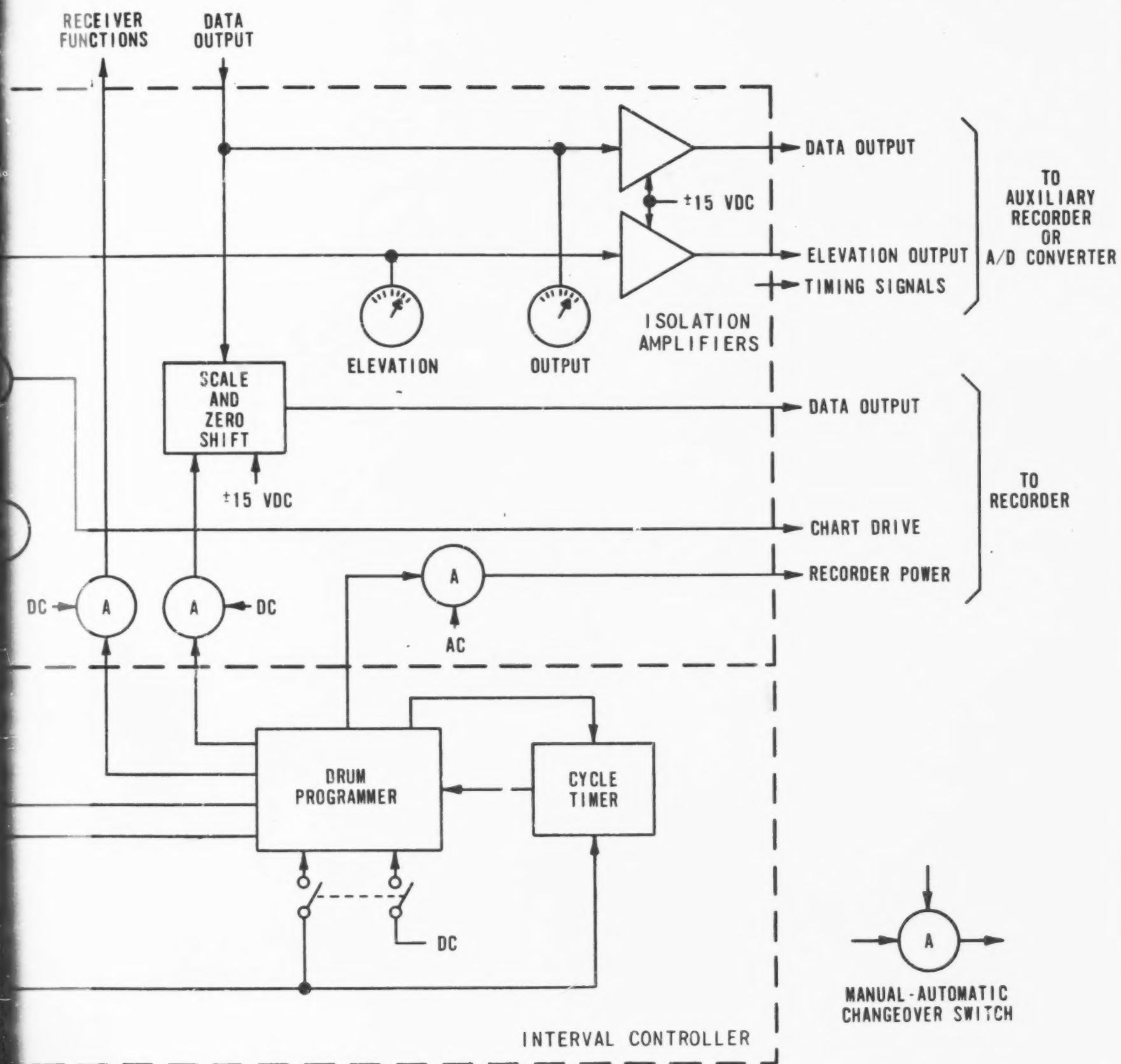


Figure 4-5. MK II Control Unit, Preliminary Block Diagram

The main control assembly will also have a visual readout of the elevation angle and brightness temperature as well as an analog data output. All peripheral equipments will be controlled through the main control assembly.

The interval controller makes possible automated, unsupervised THERMA-SONDE soundings. The interval controller includes a programmable 24-hour clock (cycle timer) which is used to start the associated drum programmer. The drum programmer stores the entire routine for automated soundings. The typical sounding sequence of the programmer would be:

- Change receiver input power status from STANDBY to ON.
- Record brightness temperature at 0 degree elevation at proper scale factor.
- Change temperature scale factor to that for temperature versus angle and center pen on recorder.
- Activate elevation scan and recorder time base drives.
- At completion of scan, revert to original scale factor, switch receiver to CALIBRATE, record calibrate level, and turn off recorder drive.
- Slew elevation back to 0 degree elevation.
- Change receiver status from ON to STANDBY.
- Reset for a new cycle and deactivate.

A typical sounding is shown in Figure 4-6. Two scale factors are used for greater resolution. The absolute temperature is measured on the $\pm 50^{\circ}\text{C}$ scale. This temperature is then used as the zero degree elevation temperature to measure the differential temperatures during the sounding. At the end of each scan, a check of calibration is made (on $\pm 50^{\circ}$ scale).

4.3.4.9 Recorder

The development of the MK II system concept during this contract has made it possible to replace the x-y recorder with a time base strip recorder. The new data reduction methods do not require a height function scan or other nonlinear scan which would require a recorder with a servo drive to track an analog input. The current methods require only a time base, synchronized with the elevation scan drive.

The recorder selected is a laboratory-industrial type strip recorder. The recorder has a 0.25 percent accuracy, a 10-inch chart width, positive chart drive which does not require a takeup reel, and an infinite-resolution servo-driven pen.

These recorders are available with enough accessory chart speeds, range scales, chart paper and attachments so that versatility and compatability are excellent and only a minimum amount of interface is required.

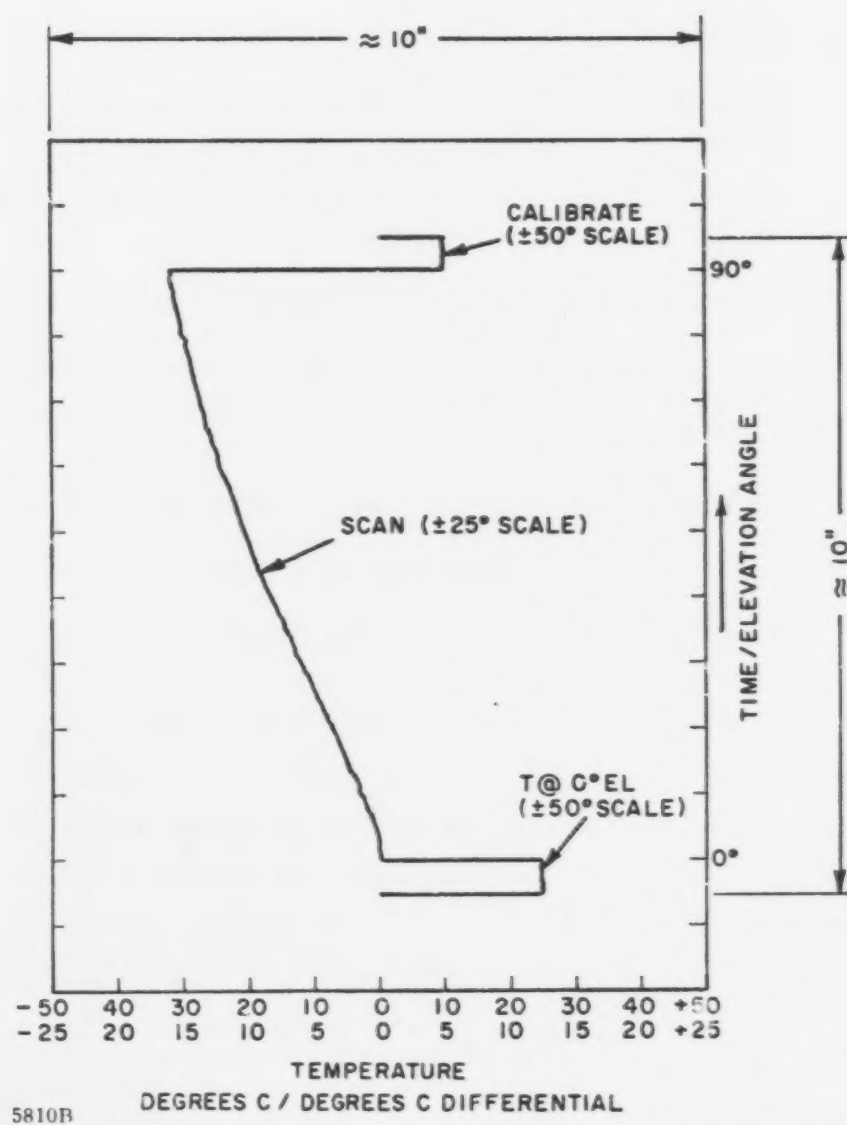


Figure 4-6. Typical Recording for Automated Sounding

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

During the early part of this contract, follow-on effort related to MK I was carried out in good order. Little more need be said of that phase except to note the relevance of certain efforts to MK II. The sensitivity improvement efforts on MK I were not only successful to the extent expected but pointed the way to still further sensitivity improvement for MK II. During the contract period, the MK I proved to be highly reliable and reasonably well suited for the making of soundings within the limits imposed by its design for manual operation and single speed scan. Field operations and additional consideration of operational requirements and study of data translation techniques made it clear that those design limits should be removed from MK II.

During the equipment requirements investigation and preliminary design at SMED, the MK II configuration evolved through a number of stages ... keeping pace with the evolution of data translation techniques and operational requirements developed by APCO and SRRC. While this process did result in some false starts, the final result is an optimized equipment configuration with major areas of detailed design completed. In this case, an optimized configuration is one which meets scientific criterion for accuracy and data format, provides simplified and/or automated operation, and is practical to fabricate and maintain. It is also believed that the design will prove to be cost effective in its application to air pollution prediction.

5.2 RECOMMENDATIONS

Sperry recommends that development of the MK II THERMASONDE proceed as expeditiously as practical in order to make the equipment available to air pollution control personnel at the earliest possible date.

Development and Fabrication of Hardware. An orderly and efficient development process for the equipment is recommended as follows:

- Breadboard, test and develop the MK II THERMASONDE receiver starting at the earliest possible date.
- Complete the electrical design of the control unit meeting the latest requirements. Breadboard and test critical control unit circuits.
- Fabricate a complete MK II THERMASONDE engineering breadboard model, using the component parts of sub-units previously developed, in the final form expected of MK II. (This unit should be suitable for complete testing of all requirements and for modification as necessary during tests to insure that all requirements are met.) Test and modify this model to meet all requirements in order to prove MK II design.
- Prepare drawings of the final design from which final field evaluation models of the proven design may be fabricated.
- Fabricate a sufficient number of MK II THERMASONDE to permit a thorough field evaluation of the operational utility of the THERMASONDE in air pollution control.

Study and Evaluation. In addition to the development and fabrication of the MK II hardware, Sperry recommends that certain study and evaluation efforts be included in an overall program:

- While the engineering model development is being completed, and even beyond that time, a continuing investigation should be carried out of the various means of implementing the techniques available for translating raw THERMASONDE data into temperature-height profiles. Presently, it seems that no single technique implementation will be optimum for all operational situations and requirements.
- Following laboratory development of the engineering model, it should be used in a limited field evaluation program to prove the basic operational utility of the MK II design.
- When the first field evaluation models become available, use these initially to carry out a thorough-going field evaluation program to prove operational utility and compatibility with then-available data translation techniques.

This recommended program, if begun immediately, could place proven operational equipment and data translation implementation techniques in the hands of operational users before the end of 1973.

APPENDIX A

BLANK PAGE

APPENDIX A

AUTOMATIC GAIN CONTROL

This section is a detailed analysis of the automatic gain control and its application in a microwave radiometer.

Gain Instability Considerations

In order to establish the stability requirements of the THERMASONDE, it is necessary to first consider the basic transfer equation of a Dicke radiometer. From Figure 1, the instantaneous output peak voltage from a square law video detector for each switch position is:

$$e_1 = G_1 D_1 (P_A + P_N), \text{ Switch Position 1}$$

$$e_2 = G_1 D_1 (P_R + P_N), \text{ Switch Position 2}$$

Since the video section of the receiver is ac-coupled, only the difference in the peak-to-peak voltage is amplified. The output of the video amplifier is then

$$e_3 = (e_1 - e_2) G_2 = G_1 G_2 D_1 (P_A - P_R)$$

and since $P = KTB$, where

K = Boltzmann's constant

T = temperature in Kelvin

B = rf reception bandwidth

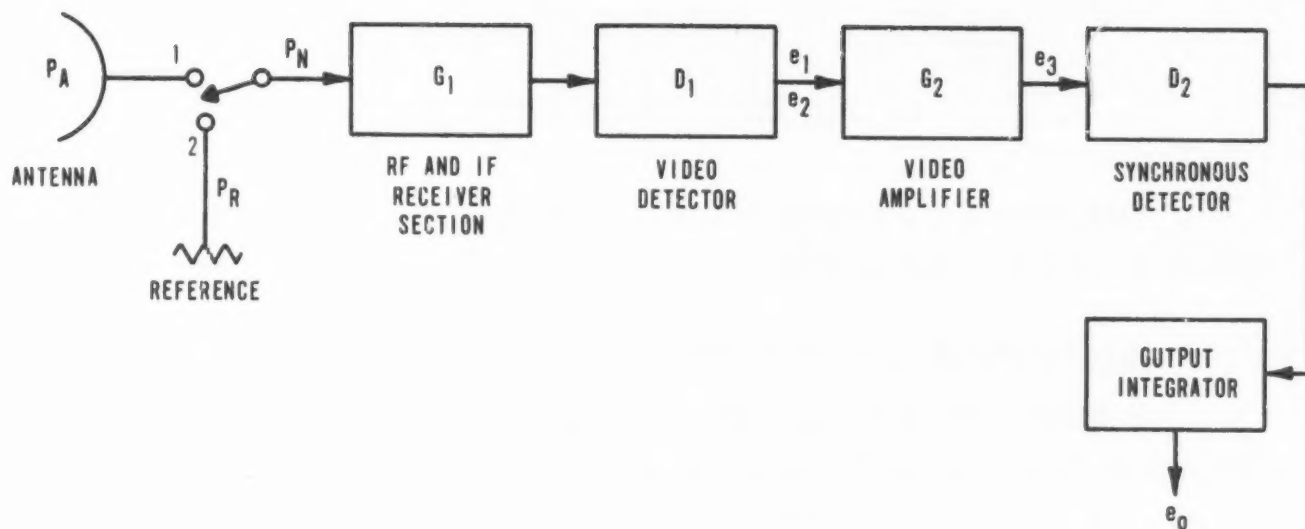
$$e_3 = G_1 G_2 D_1 KB (T_A - T_R)$$

The final average output voltage of the receiver after synchronous demodulation and integration becomes

$$E_{o(avg)} = D_2 \left(\frac{e_3}{2} \right) \left(\frac{2}{\pi} \right) = \frac{G_1 G_2 D_1 D_2 KB}{\pi} (T_A - T_R) = G' (T_A - T_R) \quad (1)$$

where

G' = resultant overall gain constant



- P_A = input power at antenna terminals
 P_R = reference power from Dicke reference load
 P_N = equivalent input noise power of the receiver
 G_1 = overall power gain of the receiver rf and if
 D_1 = video detector conversion factor, $\frac{\text{volts}}{\text{watt}}$
 G_2 = voltage gain of video amplifier
 D_2 = synchronous detector conversion factor

Figure 1. Basic Dicke Receiver

The stability criterion for the receiver can be expressed as

$$\frac{\partial E_o}{\partial G'} \Delta G' \ll \frac{\partial E_o}{\partial T_A} \Delta T_{(\min)} \quad (2)$$

where

$\Delta T_{(\min)}$ = receiver minimum detectable temperature difference

Taking differentials of Eq. (1) and substituting into Eq. (2) provides the condition

$$(T_A - T_R) \frac{\Delta G'}{G'} \ll \Delta T_{(\min)} \quad (3)$$

Eq. (3) shows that the allowable gain drift is a function of $(T_A - T_R)$ and for values of T_A near T_R the system is less sensitive to gain drift. Since the resultant overall gain constant G' is proportional to the receiver factors $G_1 G_2 D_1 D_2 B$, it is apparent that variation in any of these factors will produce a variation in the output voltage and a corresponding error in determining T_A . As an example of the gain stability required, assume that $\Delta T_{(\min)}$ is negligible and the difference between the antenna temperature, T_A , and the reference temperature, T_R , is 50 K. If a measurement accuracy of 0.1 K is desired, the overall gain (including the effects of bandwidth and detector conversion factors) must be controlled to within

$$\frac{\Delta G}{G} = \frac{0.1 \text{ K}}{50 \text{ K}} \times 100 = 0.2\% \approx 0.01 \text{ dB}$$

It is obvious that gain control must be very tight in order to achieve this degree of accuracy. Variations on the order of 0.01 dB could be produced by fine gain variation of individual components.

Eq. (3) shows that the rms variation in the receiver output due to gain variation must be very small relative to the $\Delta T_{(\min)}$ of the receiver. If the effects of receiver gain variation are included with the $\Delta T_{(\min)}$ of the receiver, the total temperature variation in the output, ΔT_T , is equal to the root-sum-square of $\Delta T_{(\min)}$ and the variation in temperature due to gain fluctuation

$$\Delta T_T = \sqrt{(\Delta T_{(\min)})^2 + (\Delta T_G)^2} \quad (4)$$

where

ΔT_G = variation in output temperature due to gain fluctuation only.

As an example, if a $\Delta T_{(\min)}$ of 0.09 K is assumed and the previous allowable gain fluctuation temperature of 0.1 K is included, the total rss variation on the receiver output for an input temperature differential of 50 K will be

$$\Delta T_T = \sqrt{(0.09)^2 + (0.1)^2} = 0.135 \text{ K}$$

This corresponds to a 50 percent increase in the effective minimum detectable temperature difference of the receiver.

These previous equations and examples are presented to show the effects of gain variation on unbalanced receiver operation and the degree of gain regulation that is required in order to achieve high measurement accuracy.

AGC Compression Ratio

There are many parameters in the receiver and AGC circuit that affect the overall performance of the system. Some of the more significant are the input AGC temperature difference to the receiver, receiver gain ahead of the AGC control loop and gain within the control loop, equivalent time constants in the receiver channel and in the control loop and the noise performance of the control loop. The most critical circuit, however, in terms of the gain control accuracy and stability is the gain controlled device or control section of the receiver. To evaluate the control accuracy, consider the block diagram in Figure 2. The output of the AGC phase detector provides a voltage whose amplitude is proportional to receiver gain. This voltage may be applied as reverse feedback AGC.

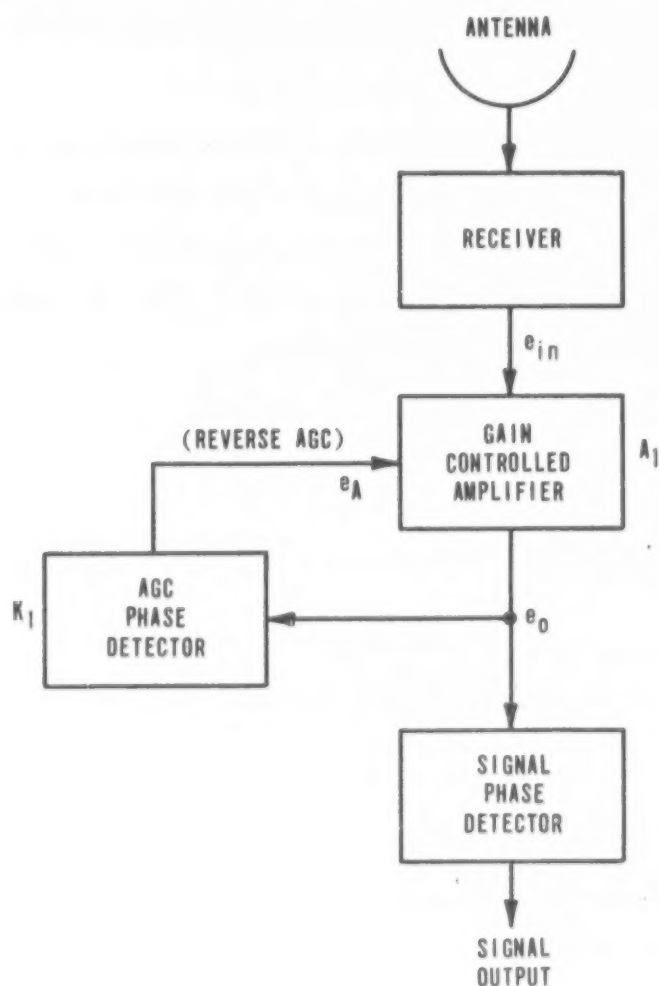


Figure 2. Receiver Gain Control Section

For the following analysis, it is assumed that the AGC signal is completely isolated from the video signal which has also passed through the gain controlled amplifier. In addition, only simple gain control functions without time constants are considered.

For the case of reverse feedback, it is assumed that the gain is inversely proportional to some power, n , of the AGC control voltage

$$A_1 = \frac{e_o}{e_{in}} = \frac{A_o}{e_A^n} \quad (5)$$

where

A_o = amplifier gain with no signal present

e_A = AGC control voltage

(NOTE: n equal to 1 would be inverse proportional feedback.)

The AGC control voltage derived from the receiver output is

$$e_A = K_1 e_o \quad (6)$$

where

K_1 = gain factor of the AGC phase detector and any other amplifiers in the control loop

Substituting Eq. (6) into Eq. (5) yields

$$\frac{e_o}{e_{in}} = \frac{A_o}{(K_1 e_o)^n} \quad (7)$$

rearranging terms

$$e_o^{n+1} = A_o / K_1^n e_{in} \quad (8)$$

Converting the input and output voltages to dB yields

$$(n+1) e_o \text{ (dB)} = 20 \log A_o / K_1^n + e_{in} \text{ (dB)} \quad (9)$$

and taking differentials of both sides gives

$$\frac{\Delta e_{in} \text{ (dB)}}{\Delta e_o \text{ (dB)}} = (n+1) \quad (10)$$

The left-hand side of Eq. (10) is known as the compression ratio, C.R. (i.e., the ratio of input change in dB divided by output change in dB). For the general case considered, then

$$\text{C.R.} = n+1 \quad (11)$$

Two gain controlled devices -- a Raytheon CK-1114 light controlled variable resistor and a National Semiconductor LM170 monolithic chip -- have been investigated to determine their equivalent values of n . The variable resistor has a value of 10.6 and the chip has a value of 65 corresponding to C.R.s of 11.6 and 66, respectively. It should be noted, however, that these represent maximum achievable values for practical gain control circuits.

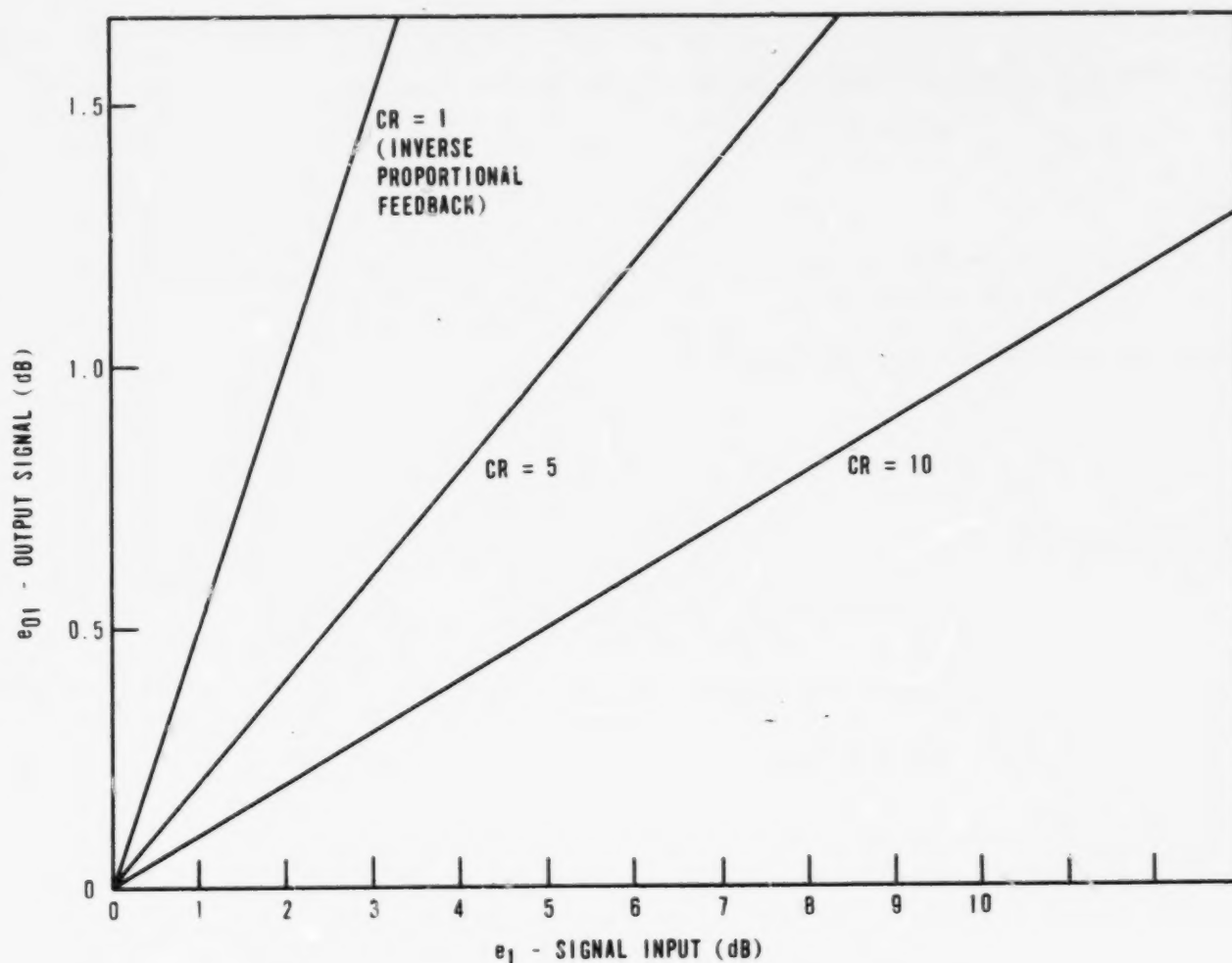


Figure 3. Receiver Compression Ratio

Figure 3 shows the defined characteristics of compression ratio. If the gain is inversely proportional to AGC voltage, n equals 1, the C.R. will be 2. Then, for example, if the input signal changes by 2 dB, the output gain controlled signal will change by 1 dB. If the output signal must be controlled to 0.01 dB as described by the example in the previous section, and the maximum variation in the input signal were 1 dB, then a C.R. of 100 would be required. As a result of the performance obtained to date with the MK 0 and MK I Radiometers, it appears that a C.R. of about 20 to 50 will be required.

Control Loop Considerations

The basic AGC system equations presented can now be expanded to include the sources of phase shift and time delay in the control loop. Also, a first order approximation to the nonlinear action of the AGC system can be made so that the theoretical performance can be predicted. Figure 4 shows a block diagram of the receiver gain control section which has been analyzed, breadboarded and tested during this program.

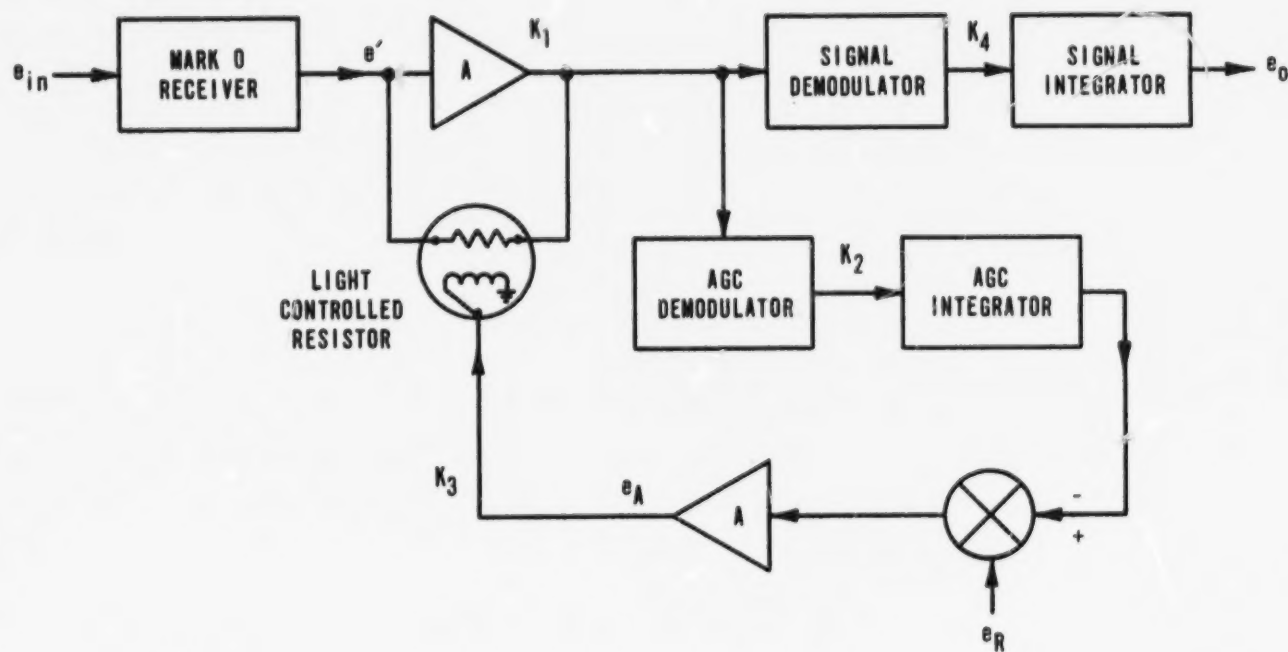


Figure 4. Receiver Gain Control Section, Simplified Block Diagram

The system equations in simplest form are as follows:

$$e_o = e' K_1 (e_A), \quad \text{for } K_4 \quad (12)$$

$$e_A = (e_R - K_2 e_o) K_3 \quad (13)$$

To approximate linear operation, small deviations in the output can be related to small deviations in e' and e_A as follows:

$$\Delta e_o \approx \frac{\partial e_o}{\partial e'} \Delta e' + \frac{\partial e_o}{\partial e_A} \Delta e_A \quad (14)$$

From Eq. (12)

$$\begin{aligned} \frac{\partial e_o}{\partial e'} &= K_1 \\ (e_A &= \text{constant}) \end{aligned} \quad (15)$$

and from Eq. (13)

$$\frac{\partial e_A}{\partial e_o} = -K_2 K_3 \quad (16)$$

Deviations in the output are related to deviations in the AGC bias through the feedback path as follows:

$$\begin{aligned} \frac{\partial e_o}{\partial e_A} &= \frac{\partial e_o}{\partial G} \times \frac{\partial G}{\partial e_A} \\ (e' &= \text{constant}) \end{aligned} \quad (17)$$

where

$$\frac{\partial e_o}{\partial G} = e'$$

In order to evaluate the partial derivative $\partial G / \partial e_A$, the gain characteristic of the control stage must be considered. Figure 5 shows the typical gain characteristic of an amplifier with a light controlled resistor as the feedback element. The equation for the straight line curve is

$$K_1 \text{ (dB)} = 20 \log K_1 = M e_A + b \quad (19)$$

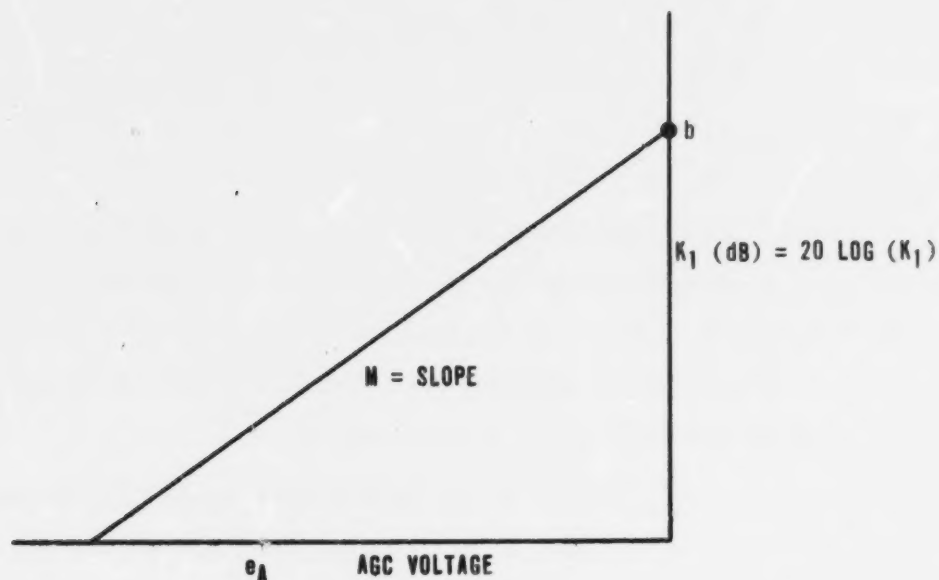


Figure 5. Typical Amplifier Gain Control Characteristics

Differentiating with respect to e_A gives

$$\frac{\partial(20 \log_{10} K_1)}{\partial e_A} = \left(\frac{20}{\log_e 10} \right) \left(\frac{1}{K_1} \right) \left(\frac{\partial G}{\partial e_A} \right) = M \quad (20)$$

and rearranging terms gives

$$\frac{\partial G}{\partial e_A} = 0.115 M K_1 \quad (21)$$

Substituting Eqs. (15), (16), (18) and (21) into Eq. (14) and rearranging the terms to obtain the output to input ratio for the gain control loop gives

$$\frac{\Delta e_o}{\Delta e_{in}} = \frac{K_1}{1 + 0.115 S K_1 K_2 K_3 e_{in}} = \frac{K_1}{1 + K'} \quad (22)$$

In the final equation, K_1 is the incremental gain of the gain controlled stage and K' is the incremental gain of the AGC loop. With this linear approximation to the control loop, it is now possible to apply conventional feedback analysis in order to determine the closed loop dynamic behavior.

The sources of phase shift and time delay in the control loop are contained in K_2 and K_3 as follows:

$$K_2 = \frac{A_2}{\tau_2 S + 1} \quad \text{and}$$

$$K_3 = \frac{A_3}{\tau_3 S + 1}$$

τ_2 is the predominant loop time constant provided by the AGC integrator and τ_3 is the time constant associated with the light controlled resistor and its drive amplifier. In addition, there are effective time constants associated with the radiometer receiver and amplifier, K_1 , due to their bandpass characteristics, but these are neglected because they are very small relative to τ_2 and τ_3 .

The circuit shown in Figure 4 has been breadboarded and tested using the MK 0 THERMASONDE as a test fixture. Both open loop and closed loop tests have been conducted to investigate stability, cross-talk and compression ratio. In general, the analysis and test results show acceptable values of gain and phase margin for compression ratios of 50 to 60. The input AGC signal-to-noise ratio to the control loop (found experimentally) must be 1.5 or greater in order to maintain adequate control loop stability which corresponds to an AGC temperature differential of 6°C or higher. The measured cross-talk is very nearly equal to the theoretical value of the cosine of the phase angle between the AGC signal and the antenna signal; consequently, the relative phase must be controlled very closely if the signal amplitude is equal to or greater than the AGC differential.

The final set of values used for the breadboard tests were as follows:

$$M = 174 \text{ dB/volt}$$

$$K_1 = \frac{A_1}{(\tau_1 S + 1)} = \frac{1}{(0.0027 S + 1)} \text{ V/V}$$

$$K_2 = \frac{A_2}{(\tau_2 S + 1)} = \frac{0.637}{(10 S + 1)} \text{ V/V}$$

$$K_3 = \frac{A_3}{(\tau_3 S + 1)} = \frac{100}{(0.02 S + 1)} \quad \text{V/V}$$

$$e_{in} = 0.5 \text{ volts, P-P}$$

To examine the stability and control performance of the AGC system, the open loop gain and phase versus frequency was plotted using the above values and the results were compared with open loop measurements of the breadboard setup. The open loop transfer function from the previous equation is

$$GH = 0.115 M K_1 K_2 K_3 e_{in} \quad (23)$$

$$= \frac{1270}{(0.0027 S + 1)(10 S + 1)(0.02 S + 1)}$$

The open loop performance of the control system for both the theoretical case and the measured results is shown in Figure 6. The frequency is shown in Hz rather than the complex frequency, S , in order to simplify the comparison. As may be noted, both gain and phase curves track rather closely which shows that the differential method of approximating the nonlinear gain control action is valid. The only significant difference to be observed in the results is that the gain and phase in the breadboard setup rolls off faster at high frequency than the theoretical results show. This is attributed to higher frequency and higher order roll-off circuits in the breadboard equipment which are not accounted for in the analysis. However, for either case, the phase margin at the unity gain crossover is approximately 45 degrees which is acceptable providing the rate of roll-off does not become too large. The open loop gain of 1270 is the AGC compression ratio. For example, a change in the input signal of 10 dB would be regulated to a change of less than 0.01 dB at the output. However, it must also be noted that the open loop gain is a function of the input signal level and as the signal level decreases, the loop gain decreases and the compression ratio decreases. The loop gain is high enough, however, so that good regulation can be achieved and this has been demonstrated in the breadboard tests.

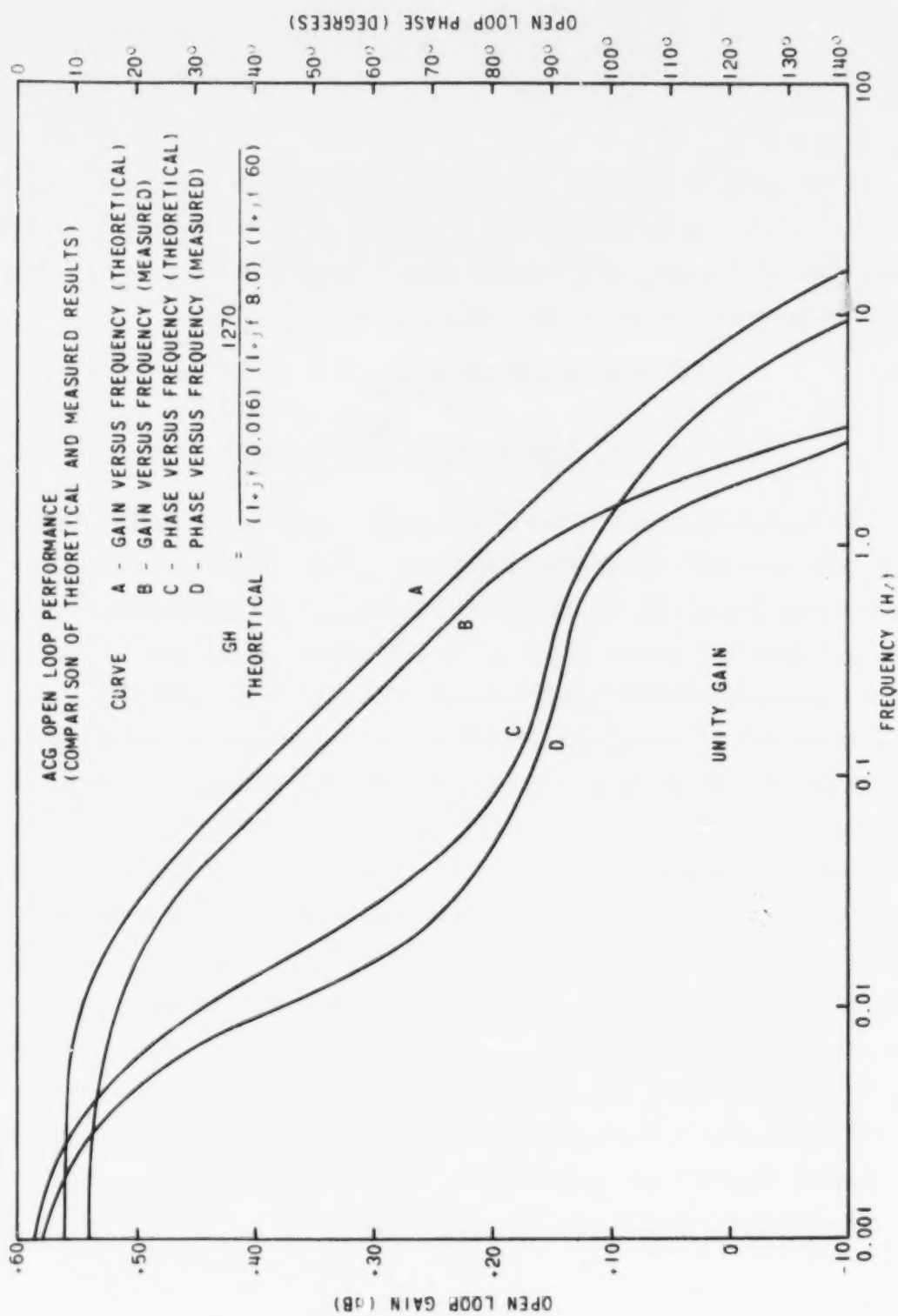
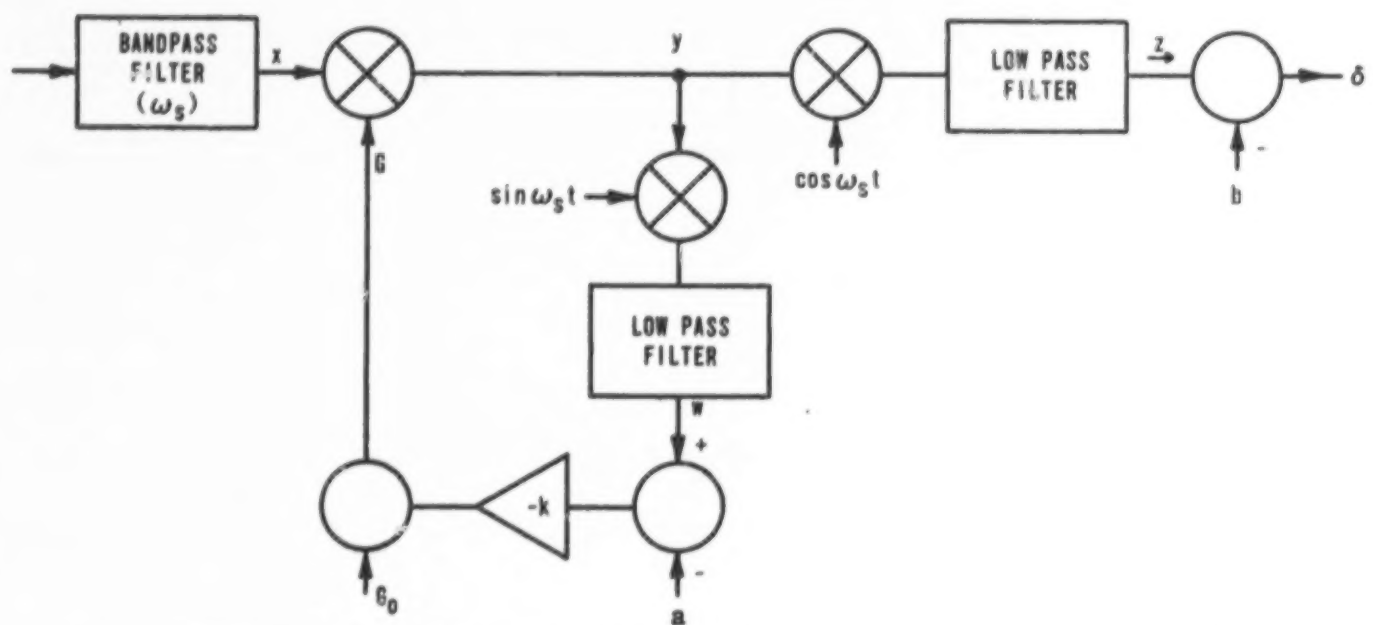


Figure 6. ACG Open Loop Performance (Comparison of Theoretical and Measured Results)

Analysis of Phasing Errors

The AGC portion of the receiver may be represented as shown in Figure 7. The signal at X is a square wave modulated AGC signal, ΔT_A , at a phase angle of θ^0 , plus a square wave modulated antenna signal, ΔT_S , at a phase angle of $90^0 + \theta + \phi$. Note that sine and cosine functions are used as the modulation and demodulation functions. These continuous functions give excellent approximations to the problem and eliminate the difficulty of representing square waves analytically.

$$X = \Delta T_A \sin(\omega_s t + \theta) + \Delta T_S \cos(\omega_s t + \theta + \phi)$$



- θ = Phase error of both ΔT_S and ΔT_A with respect to sine and cosine demodulator functions
- ϕ = Deviation of phase between ΔT_S and ΔT_A from 90^0
- G_0 = Desired amplitude gain
- ΔT_A = AGC differential coupled into receiver
- ΔT_S = Difference between antenna and chopper temperatures
- a = AGC reference value
- b = Output signal value with no errors (i. e. , $\delta = 0$)
- δ = Measurement error due to phasing errors

Figure 7. Systematic Representation of AGC

Referring to Figure 7 (when no phase errors are present),

$$Y = GX \tag{24}$$

If X is demodulated by $\sin \omega_s t$ and filtered (no phasing errors), then

$$a = G_o \Delta T_A \sin^2 \omega_s t \Big|_{\text{LPF}} = \frac{1}{2} G_o \Delta T_A \quad (25)$$

and if X is demodulated by $\cos \omega_s t$ and filtered (no phase errors), then

$$b = G_o T_s \cos^2 \omega_s t \Big|_{\text{LPF}} = \frac{1}{2} G_o \Delta T_s \quad (26)$$

Hence, a and b are the values that would appear at W and Z if no phase errors existed.

Now, consider the signal at X to contain phase errors as stated in Figure 7.

$$X = \Delta T_A \sin(\omega_s t + \theta) + \Delta T_s \cos(\omega_s t + \theta + \phi) \quad (27)$$

and

$$W = Y \sin(\omega_s t) \Big|_{\text{LPF}} \quad (28)$$

$$Z = Y \cos(\omega_s t) \Big|_{\text{LPF}} \quad (29)$$

Expanding Eq. (28),

$$W = G \left| \Delta T_A \sin(\omega_s t + \theta) + \Delta T_s \cos(\omega_s t + \theta + \phi) \right| \sin(\omega_s t) \Big|_{\text{LPF}} \quad (30)$$

$$= G \left| \frac{1}{2} \Delta T_A \cos \theta - \frac{1}{2} \Delta T_s \sin(\theta + \phi) \right| \quad (31)$$

Gain changes in the AGC due to phase errors are

$$\Delta G = -k(W - a) \quad (32)$$

and

$$G = G_o + \Delta G = G_o - k \left\{ \frac{G}{2} \left| \Delta T_A \cos \theta - \Delta T_s \sin(\theta + \phi) \right| - \frac{G_o}{2} \Delta T_A \right\} \quad (33)$$

which simplifies to

$$G = \frac{G_o \left| 1 + \frac{k}{2} \Delta T_A \right|}{1 + \frac{k}{2} \left| \Delta T_A \cos \theta - \Delta T_s \sin(\theta + \phi) \right|} \quad (34)$$

Now, assuming $k \gg 1$,

$$G \cong \frac{G_o \Delta T_A}{\Delta T_A \cos \theta - \Delta T_s \sin(\theta + \phi)} \quad (35)$$

Now, considering the error at Z,

$$Z = GX \cos \omega_s t \Big|_{\text{LPF}} \quad (36)$$

$$Z = \frac{1}{2} G \left[\Delta T_s \cos(\theta + \phi) + \Delta T_A \sin \theta \right] \quad (37)$$

Substituting Eq. (35)

$$Z = \frac{1}{2} \frac{G_0 \Delta T_A \left[\Delta T_s \cos(\theta + \phi) + \Delta T_A \sin \theta \right]}{\left[\Delta T_A \cos \theta - \Delta T_s \sin(\theta + \phi) \right]} \quad (38)$$

The fractional error in signal output is

$$\frac{\delta}{b} = \frac{Z - b}{b} = \frac{Z}{b} - 1 \quad (39)$$

Substituting Eqs. (26) and (38) into Eq. (39),

$$\frac{\delta}{b} = \epsilon = \frac{\Delta T_A \left[\Delta T_s \cos(\theta + \phi) + \Delta T_A \sin \theta \right]}{\Delta T_s \left[\Delta T_A \cos \theta - \Delta T_s \sin(\theta + \phi) \right]} - 1 \quad (40)$$

Hence, ϵ is the fractional temperature measurement error due to crosstalk in the AGC and signal channels.

General conclusions that can be drawn from Eq. (40) are:

1. The term $\Delta T_A \sin \theta$ is a constant as long as ΔT_A and θ are constant. This is a fixed bias error which can be balanced with dc.
2. $\cos(\theta + \phi)$ and $\cos \theta$ terms are within 0.1 percent of unity for all phase errors less than 2 degrees and cannot significantly contribute error to the output for smaller error angles in the range of 1 degree or less.
- ∴ For phase angle errors less than 2 degrees, the variable part of Eq. (40) becomes

$$\epsilon' = \frac{\Delta T_A \left[\Delta T_s \right]}{\Delta T_s \left[\Delta T_A - \Delta T_s \sin(\theta + \phi) \right]} - 1 = \frac{\Delta T_A}{\Delta T_A - \Delta T_s \sin(\theta + \phi)} - 1$$

This equation is similar to Eq. (35) which indicates that the variable output error is due almost entirely to spurious gain changes produced by the term $-\Delta T_s \sin(\theta + \phi)$ which is signal crosstalk into the AGC circuits.

The phase error ϕ would be produced by mechanical misalignment in the 2-phase chopper which is not subject to variation once properly aligned. The phase error θ would be produced by mechanical misalignment of the reference generator on the chopper and by differential phase shifts in the bandpass filters for signal and reference. Since bandpass filters may change phase characteristics slightly with temperature variations, it is important that the filters have identical characteristics so that differential phase shifts cannot occur.

APPENDIX B

BLANK PAGE

APPENDIX B

MEASUREMENT ERROR BUDGET

Section 4.3.4.1 of the preliminary design listed the major sources of error in measuring the brightness temperature. Following is a detailed discussion of those errors.

Frequency of Operation

At 54.5 GHz, the maximum oxygen brightness temperature slope is about 25.5°C per GHz. Thus, a local oscillator error of 100 MHz could produce a measurement error of 2.55°C. Newly developed solid-state Gunn oscillators are available which can provide excellent frequency stability. Typical frequency characteristics are:

Frequency Vs temperature	2 MHz/°C
Frequency Vs supply voltage	10 MHz/0.4 volt change

Hence, by temperature controlling the source to $\pm 1^\circ\text{C}$ and using a well regulated power supply (0.0001 percent line, 0.0004 percent load and 0.005 percent temperature coefficients are available), a frequency stability better than 2.5 MHz appears practical under the extreme variations in the ambient temperature and line voltages applicable to MK II.

Beam Pointing Accuracy

The beam pointing accuracy is a function of mechanical alignment to a reference plane and the position accuracy of the elevation drive. A design goal error of $\pm 0.2^\circ$ of arc, rss, has been established as a working goal for combined boresight and mechanical errors. A conservative number for the brightness temperature variation as a function of elevation angle is 0.4°C per degree arc. The resultant temperature error for a 0.2° arc error is 0.08°C.

RMS Receiver Noise

The rms receiver noise of 0.09°C is based on the rms noise of MK I after the recent sensitivity improvements. A design goal of 0.05°C for MK II is based on best diodes, a new, lower noise local oscillator, and reduced front-end losses.

Recorder Accuracy

Vendor data on applicable recorders for MK II shows an accuracy of 0.25 percent full scale. For a 20°C differential brightness signal, the recorder error would be 0.05°C .

Chopper Temperature Correction Computer

The chopper temperature computer consists of a precision current source and platinum wire temperature sensor. The maximum current variation is less than 1.0 microamp or about 0.10 percent, and the maximum sensor deviation from linearity is 0.05 percent. Hence, the maximum error would be approximately 0.15 percent. This would correspond to a maximum error of 0.075°C at the highest chopper temperature of 50°C .

AGC Source Control

The AGC differential temperature is controlled by a differential temperature controller. The total errors due to sensor tracking, time lags, and sensitivity of the zero voltage switch are calculated to be 0.1 percent. For a 20°C differential temperature, the maximum measurement error becomes 0.02°C .

AGC Compression

Vendor data and laboratory results indicate that a compression ratio of 50 is practical in a gain-controlled amplifier. Assuming a 20 percent change in receiver gain, the resultant error is 0.08°C . (It should be noted that gain changes as large as 20 percent have never been noted in MK I or MK 0.)

DC Output Drift

The output stage of the receiver will be subject to dc drift. The ICs chosen exhibit a maximum offset of 250 microvolts per year. For a 30 millivolt per °C scale, this is an error of 0.015°C.

Calibration Error

The calibration error is difficult to ascertain. From past experience with MK I and MK 0, a calibration error of 0.2°C would seem to be the best that can be expected.

Phase Errors

The measurement error due to phasing in the AGC and signal channel demodulators can become very large for small phase errors. Evaluation of the system equation, from Appendix A Eq. (40), for "Crosstalk" in the quadrature channels results in the following expression:

$$\epsilon = \frac{\Delta T_A [\Delta T_S \cos(\phi + \theta) + \Delta T_A \sin \theta]}{\Delta T_S [\Delta T_A \cos \theta - \Delta T_S \sin(\theta + \phi)]} - 1$$

where

ϵ = Fractional temperature measurement error due to crosstalk in AGC and signal channels

ΔT_A = AGC differential coupled into the receiver

ΔT_S = Difference between antenna and chopper temperatures

θ = Phase error of both ΔT_S and ΔT_A with respect to sine and cosine demodulation functions.

ϕ = Deviation of phase between ΔT_S and ΔT_A from 90 degrees

Assuming the two signals are quadrature modulated ($\phi = 0$), $\Delta T_A = 10^\circ\text{C}$, and $\Delta T_S = 20^\circ\text{C}$, then a phase error (θ) of 0.47 degree of arc will produce a measurement error of $\Delta T_S \epsilon = 0.42^\circ\text{C}$. A larger ΔT_A or smaller error in θ will reduce this error.